ARCHITECTURE & ENGINEERING

SPSUACE
1832

Volume 5
Issue 2
June, 2020

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eISSN: 2500-0055

Architecture and Engineering

Volume 5 Issue 2

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DOI: 10.23968/2500-0055-2020-5-2-03-07

Architecture

THE ROLE OF HERITAGE TOURISM IN PRESERVING HISTORICAL BUILDINGS IN PALESTINE (CASE STUDY OF THE PASHA'S PALACE, GAZA)

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Abstract

Introduction: Heritage tourism is often rooted by historic buildings. These powerful, tangible connections to our past are the ways in which people today come in touch with the past. Heritage buildings are also increasingly accepted as important venues linking a new generation with an older one, and thus as places to be used for heritage tourism. Revitalizing old neighborhoods — the buildings and the landscape — ensures that our quality of life is improved and that community cohesion is maintained. The Palestinian city of Gaza is mainly associated with conflicts and wars; however, its cultural side is typically hidden behind that news. But decades of uprisings, war and political turmoil have inflicted a heavy toll on its rich archaeological heritage, exposing it to looting and destruction. **Methods:** This article follows the scientific and engineering analysis as a way to deal with the mentioned problem by studying different factors affecting the architectural heritage of the Pasha's Palace in Gaza. **Results and discussion:** The article analyzes the functions of the complex, identifies and systematizes factors affecting the architectural and archaeological heritage of the old city of Gaza, and discusses the pros and cons of using the Al-Pasha Palace complex as a museum based on the strategies of the Burra Charter.

Keywords

Heritage tourism, conservation, maintenance, restoration, adaptation.

Introduction

The city of Gaza is considered one of the oldest cities. A sliver of land on the Mediterranean, Gaza was a major trade route between Egypt and the Levant going back to ancient times, with its roots extending to the third millennium BC (Lembaund, 1987; Suwaidan, 2004). The city was a cradle for many civilizations, including Canaanite, up to the Byzantine and Christian periods, and then to the Islamic era and subsequent periods, i. e. the Mamluk and Ottoman periods. All these periods have affected its development and left us a unique legacy and cultural heritage represented by numerous historical buildings. Throughout history, wars caused much destruction to archaeological and historical sites (Alnmara and Al-Qeeq, 2010). The Gaza Strip stays in the headlines with tragic regularity, while fabulous archaeological riches become buried under the ground. Despite the fact that indiscriminate violence destroyed some parts of the city, there are still historical attractions and landmarks to be seen. Palaces are the most important buildings of the Islamic architecture, characterized by unique methods of construction, art, decoration and inscriptions. Besides, they represent an impressive record of all stages of Islamic architecture development, particularly in Palestine.

Methods

Over time, we may lose some part of the cultural heritage since many ancient buildings and structures are built of sandstone. Sandstone and marble are the main materials that were used in Gaza city in antiquity to construct buildings, make sculptures to decorate facades, etc. However, such buildings are exposed to environmental damage (Palestinian Government, 1947). Besides, repeated wars have the biggest role in destroying cultural heritage, especially the Pasha's Palace complex.

The study focuses on the urban and architectural character of the Pasha's Palace in Gaza city and the factors that affected the complex (political, economic and social factors).

The study addresses the architectural and functional transitions of the Pasha's Palace in Gaza city during different historical periods from the Mamluk period until the end of the 20th century. At the beginning of the 21st century, it was rehabilitated as a museum. The article presents a detailed study of the monument use throughout history and describes the extent, to which it was affected by various political, economic, cultural and social factors. After the analysis and evaluation of the Pasha's Palace study results, we will offer some recommendations helping to save this important historical monument from extinction.

The purpose of the study is to analyze the impact of adverse environmental factors on the preservation of cultural heritage and examine research methods for the preservation of the architectural and archaeological heritage of the Al-Pasha Palace complex. The corresponding tasks include: consideration of the main anthropogenic and natural factors destroying cultural heritage; consideration of measures used for the preservation of cultural heritage.

Figure 1. Qasr al-Ridwan (Pasha's Palace). Lithograph, 1819 (Travelogues, 2014).

Figure 2. Pasha's Palace, 2020 (Ministry of Tourism and Antiquities, 2013).

Objectives:

1. To identify features for the formation of a scientific approach to the restoration of monuments of Arab architecture and determine the degree of knowledge regarding the architectural and archaeological heritage of Gaza (e.g. regarding the Al-Pasha Palace complex).

2. To identify stages of Al-Pasha Palace complex evolution.

3. To analyze the experience in implementing programs to preserve the heritage of Palestine, taking into account regulatory documents adopted at the international and national level (in particular, the United Nations Development Program (UNDP) for the transformation of the Pasha's Palace into a museum).

Subject matter of the study

The Al-Pasha palace (also known as the Palace of Al-Radwan) having the features of the Mamluk era is located in the Daraj district in the eastern part of old Gaza. This district is considered the richest in having historical buildings in the city. The palace reflects traditions, signs of the civilization and progress witnessed there in earlier times.

Figure 3. Historical stages of Al-Pasha Palace complex evolution (Ministry of Tourism and Antiquities, 2013).

Architectural description of the palace. The way this palace was built represents the philosophy and features of Islamic architecture. The complex includes two separate buildings with a yard in between, in addition to the front yard of the two-story old building.

Figure 4. Pasha's palace (Ministry of Tourism and Antiquities, 2013).

DOI: 10.23968/2500-0055-2020-5-2-03-07

Figure 5. The lion's emblem, the Mamluk period (Ministry of Tourism and Antiquities, 2013).

The architectural elements that signify the building are represented by geometrical decorations in the fronts and entrances (Fayad, 2010). Various shapes (mostly star shapes and sharp curves) give prominence to the frames of the entrances. The main entrance to the palace is located on the southern facade of the northern building. It is decorated with beautiful geometric motifs inscribed in stone, particularly, with a rectangle stone with an image of two lions on the two sides, which is the symbol of the fourth Mamluk Sultan, Al-Zaher Baybars. Baybars was one of the military commanders in the battle of Ain Jalut, during which the Mamluk forces defeated the Mongols in 1260. The Mamluks were a Muslim dynasty that ruled Egypt and much of the Levant from their base in Cairo from the 13th through the 15th centuries.

The second story is largely Ottoman construction. The Pashas of Gaza administered their realm from this palace following the rapid conquest of the Middle East by the Ottomans during the late 15th and early 16th centuries. The second floor of the two buildings can be reached through external stairs for each building. Studies show that there is an underground floor requiring renovation under the southern building that disappeared and was covered by soil.

Influence of political factors on the buildings of the Pasha's Palace complex throughout history: The Al-Pasha Palace was exploited by occupiers during different historical stages of Gaza city since it is one of the largest and most beautiful buildings in the city (Wafa, 2005) This made the palace a target for destruction during military conflicts, which affected its architectural and planning structure.

1. It was exploited during the Mamluk era (1260–1517 AD) as the headquarters of the Gaza Prosecution (military headquarters).
2. During the Ottoman era (1517–1923 AD), it was the governor's residence (Al-Pasha Palace).
3. In 1799 AD, the Pasha's Palace was occupied by the French campaign for a few days (Napoleon Castle).
4. During the period of the British Mandate of Palestine (1918–1948 AD), it was a police station (called Deboya).
5. During the rule of the Egyptian administration in Gaza (1948–1967 AD), it was used as a school administration building.
6. During Israeli occupation (1967–2005), it was abandoned but served as a target during conflicts and wars.
7. During the rule of the Palestine government (2005–2009), it was abandoned but since 2010 is has been used as an archaeological museum.

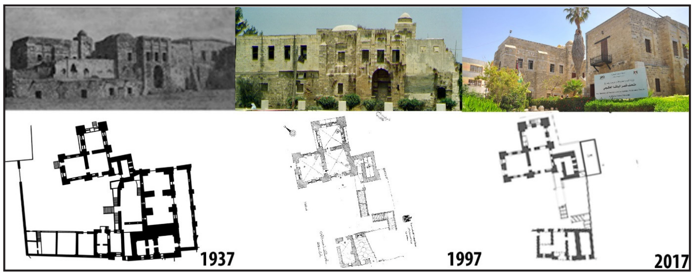

Figure 6. Buildings of the Al Pasha Palace complex affected by war.

Role of international and local institutions in the preservation of the historical monument:

1. Role of international institutions in the preservation of the historical monument: Within the United Nations Development Program (UNDP), a project was funded by a grant from the German Development Bank (KfW) for the transformation of the Pasha's Palace into a museum (Mitri Abu Aita, 2004). During the first phase of the project, workers landscaped the museum grounds, installed new doors, windows and gates, and restored the facade of the Pasha's Palace. In the second phase of the project, display cases and other appropriate furniture were installed in the museum. The smaller building in front of the palace was also renovated for use as a gateway to the museum.

2. Role of local institutions in the preservation of the historical monument: The Ministry of Tourism and Antiquities seeks to exercise its primary function of preserving and consolidating the features of Palestinian civilization and culture. The ministry uses its best efforts to ensure the success of the project in partnership with the UNDP Foundation.

Methods of building conservation (Australia ICOMOS, 1999). According to the Burra Charter, there are five main strategies in conservation:

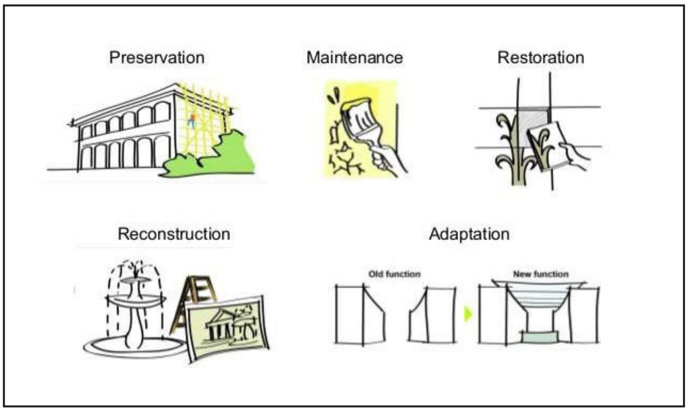

Figure 7. Methods of building conservation (Australia ICOMOS, 1999).

The project for the restoration and rehabilitation of the Pasha's Palace in 2015:

1. Restoration of the northern building of the palace complex.

Figure 8. Northern building of the Pasha's Palace complex before and after restoration (Ministry of Tourism and Antiquities, 2013).

2. Restoration of the southern building of the palace complex.

Figure 9. Southern building of the Pasha's Palace complex before and after restoration (Mitri Abu Aita, 2004).

Benefits of heritage building conservation: The preservation of heritage buildings is a vital component of urban revitalization efforts. The conservation of heritage buildings can help us all in an impressive variety of ways.

Results and discussion

1. We identified the historical stages of Al-Pasha Palace complex evolution in the 20th century as a result of repeated wars.
2. We analyzed the experience in the restoration and preservation of the architectural and archaeological heritage of Gaza through the rehabilitation of the Al-Pasha Palace complex.
3. We studied the experience of joint activities of national and international organizations in implementing comprehensive programs for the restoration of the architectural and archaeological heritage in the historical cities of Palestine (in particular, the United Nations Development Program (UNDP) for the transformation of the Pasha's Palace into a museum).
4. We identified and systematized factors affecting the architectural and archaeological heritage of the old city of Gaza, represented by aspects of the political, environmental, social and economic nature.
5. We emphasized the importance of the rehabilitation of the monument as a national museum to highlight its historical significance.
6. We also identified possible pros and cons, constraints, and effects of strategies in building conservation according to the Burra Charter with regard to the Pasha's Palace.

Below we discuss the possible pros and cons, constraints, and effects of such strategies:

Table 1. Pros and cons of the strategies for the Pasha's Palace Museum (Gaza) according to the Burra Charter.

Pasha's Palace Museum	Pros	Cons
1. Preservation	• The building form as it has evolved over time can be retained.	• Less flexibility: it may be more difficult to accommodate future development since the building's existing state has to be preserved (this applies especially to its use as a museum).
2. Maintenance	• Stabilizes building conditions.	• Maintenance cannot solve any severe structural problems and it is also costly (due to the siege and economic problems of Gaza city).
3. Restoration	• Restores the property to an architecturally 'pure' state and therefore is a better representation of a particular historical era. Cultural value can be fully reflected.	• It is common to alter a building to reuse it. These alterations can also be considered part of the building's history and often reflect the aesthetics of certain periods. To what extent should such alterations be tolerated and preserved? • May require techniques or materials that are lost or hard to find. Technically challenging.
4. Reconstruction	• Facilitates interpretation by recreating important structures or details.	• New material is introduced. • The authenticity of the building is lowered.
5. Adaptation	• The building can function as part of society rather than staying as an abandoned building.	• Changes in structure may have to be made. The authenticity of the building is lowered.

DOI: 10.23968/2500-0055-2020-5-2-03-07

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THE "BAROQUE SKYLINE" IN NAPLES. STRUCTURAL STUDIES ON 16TH AND 17TH CENTURY DOMES IN TERMS OF FORM AND STABILITY

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Abstract

Introduction: Walking through the streets of the historic center of Naples and taking a glance at the sky, you may notice that its skyline is determined by the countless peculiar architectural elements, the domes precisely, that stand out from the context. **Purpose of the study:** The study aims to investigate the Neapolitan domes of the 16th and 17th centuries, focusing on the role of geometry and the close relationship between form and stability in the construction of this type of vaulted structures. **Methods:** Geometric surveys and in-situ investigations are used to define the shape of the domes. The study of the constructive solutions is based on the analysis of the original documents describing the works carried out as well as the analysis of several structural components that constitute the domes. This is related to ancient treatises and comparison, as far as possible, with similar buildings. Finally, to describe the mechanical behavior of these constructions, reference is made to the Modern Limit Analysis Theory developed by J. Heyman and applied to masonry structures in order to determine their degree of safety. **Results:** The approach set out can help to avoid improper restoration interventions on such historical artefacts. For good restoration work, it is absolutely indispensable to deeply investigate the geometrical and constructive aspects of a building, as well as its mechanical properties, in order to avoid approaches and methods of structural analyses far from the real behavior of these masonry structures.

Keywords

Baroque, construction history, masonry domes, limit analysis, restoration.

1. Introduction

The domes in Naples represent a cultural asset scattered throughout the city and characterized by precise examples belonging to several historical periods that contribute to testify the different construction phases of the urban context. Among all of them, the present work focuses on the Neapolitan domes of the Baroque period. Numerous studies have been previously conducted on this topic. Since 1998, some researches, carried out in Naples, have concerned the domes. In that year, a study was performed by a group of researchers, coordinated by Salvatore Di Pasquale, in order to promote a multidisciplinary approach involving not only historians but also experts in structures. Later, in 2005, another research was carried out, funded by the Ministry of University and Research, on the domes in Campania (Casiello, 2005), where they reported cognitive investigations and issues of conservation, and also, a further research program on the dome structures between the 15th and 16th centuries in Campania is being carried out coordinated by prof. Valentina Russo (de Martino, 2017). To date, these investigations are mainly focused on the historical and restoration aspects as well as the drawing and representation of vaults and domes resulting in the fragmentary and compartmentalized form, without belonging to a broader cognitive field concerning the cultural heritage. More than in other Italian cities, the Neapolitan Baroque is marked as a period of transition from the certainties of the 16th century to the doubts of the 17th century with tensions that are reflected in the architectural language. All this information, which can be deduced from a detailed analysis of these historical compounds, must converge in the same process aimed at the transmission of values and the conservation of the buildings. Namely, when dealing with the substantial separation between compositional aspects (formal, spatial) of buildings and structural ones, which appears from contemporary studies on this issue, there is a need for an interdisciplinary approach to assess the stability of these historical structures and avoid inappropriate consolidation intervention. The study aims to contribute enriching the knowledge on design and construction techniques adopted for the domes built in the Neapolitan Baroque period, whose studies up to now are still incomplete. The innovative character of the research is configured to contribute to broadening the knowledge of these architectural elements by making available to the scientific community the proper tools to intervene in a not invasive manner on these historical artefacts and to deal with the problem of preservation of the architectural heritage.

DOI: 10.23968/2500-0055-2020-5-2-08-16

2. Literature review: notes on the Neapolitan background

A complete understanding of historic buildings — how these structures were designed by their builders, the knowledge of their positioning and the rules used for the dimensioning of the structural elements — is necessary to conduct correct static analyses by employing currently available means and, at the same time, absolutely consistent with the original design of the structure (Cusano, 2019). In this section, with a special emphasis on the Neapolitan context, an excursus on the historical premises that characterized the development of theories and methods for the study of historical structures in masonry is presented, with remarks regarding the contribution given during the centuries by treatises. Traditionally, the ancient master builders used structural rules (geometric and arithmetic) to size the constructions. Knowledge of the fundamental properties of masonry structures was acquired by the experience in construction and by the use of scale models: the set of rules and their fields of application constituted, in every age, the 'theory of structures' (Huerta and De La Cuerda, 1998). At the end of the 17th century, the science of mechanics had acquired sufficient development and scientific justification for these technical processes was needed. As known, the birth of the analysis of masonry vaulted structures occurred at the end of the 17th century, in England (Robert Hooke and the theory of the catenary) and France (De La Hire, Bélidor) at the same time. In the 18th century, the coexistence between the traditional calculation and the scientific one, that began in the 17th century and lasted till a time when masonry dome constructions were abandoned at the beginning of the 20th century, continued. Architects and engineers with more scientific background feel, more and more, the need to justify their projects according to the laws of mechanics. However, conscious or unconscious, the reference to the validity of their theories and their calculations can be found in traditional rules, coding the proportions of existing buildings. The next major step in the theory of masonry arch takes place in the second half of the 20th century and consists in the application of the recently developed limit analysis (Heyman, 1966, 1995).

In the Neapolitan context, numerous studies and essays show the greatest attention to this topic by scientists who deal with the study of the behavior of domes both in general terms and with reference to specific monuments (Aveta, 2005). Among these, the essays by G. A. De Fazio (1813), N. D'Apuzzo (1831), and those by F. P. Tucci (1832, 1884) are cited (Figure 1). In the D'Apuzzo's treatise, the most advanced studies in the research of the pressure curve are also mentioned; in particular, he refers to the studies performed by De La Hire, Frezier, Durand, Gauthey, Couplet, Perronet and Mascheroni. The re-edition of the treatise by N. Cavalieri San Bertolo (1840) is also published in Naples, focusing on the distribution of technical culture.

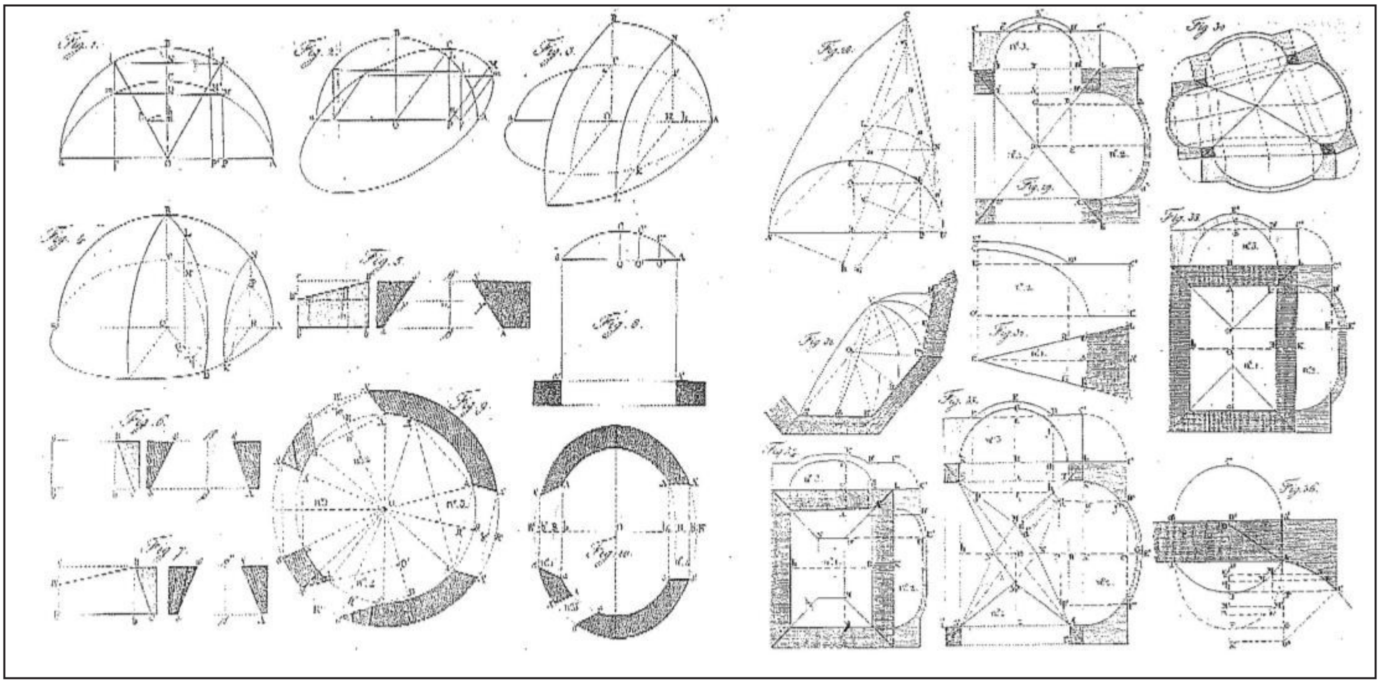

Figure 1. F.P. Tucci. Della misura delle volte rette ed oblique, Napoli 1832, Tav. I and Tav. IV.

Exactly one century earlier, the most important scientific writings concerning structural topics were written in Naples by Vincenzo Lamberti and Nicola Carletti.

V. Lamberti wrote his *Statica degli edifici* (Lamberti, 1781), in which he discusses the issue of construction theory in Naples at the time. In the last part of his essay, the author focuses on the possible causes of static failures in buildings by detecting, among them, weakness of foundations, shaking, overload, bad construction practice, and ancientness (Figure 2). Lamberti also introduces a

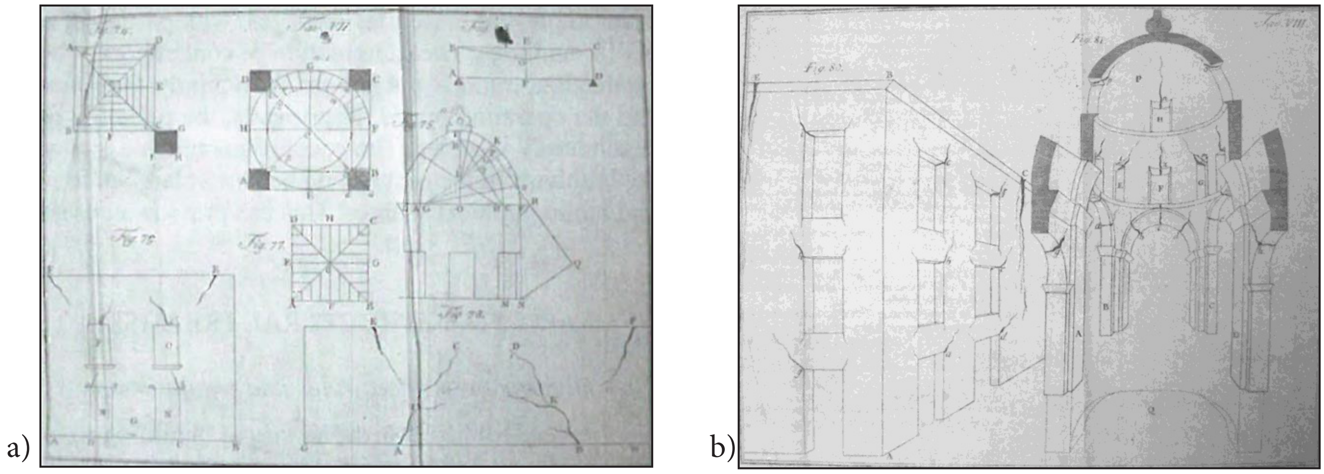

Figure 2. V. Lamberti. *Statica degli edifici.* (a) Tav. VII, (b) Tav. VIII.

corresponding type of cracking for each of the identified causes and, even if the problem of vaulted structures is not specifically dealt with, the case of cracking in arches bearing a dome is addressed (De Martino and Russo, 2005).

Carletti also addressed the study of domes, focusing on the risks associated with this type of structure, which he considered “by nature, light, imperfect, expensive and dangerous” being the result of a “joint of several pointed arches”. He classifies these structures into dome vaults and hemispherical vaults on the basis of their resistance to vertical stresses.

In the second half of the 19th century, the contribution of E. Folinea (1855) can be mentioned: in his essay, he focuses on the interpretation of the crack pattern of ancient buildings and the most adopted restoration interventions. He also studies the problem of damage caused by horizontal thrusts in buildings covered by masonry vaults. In 1855, the treatise of F. De Cesare was published, in which the knowledge on the construction of the vaults was developed in a fairly complete way. In his work, there are references to the evolution of the theories of their proportioning, with reference to the Rondelet’s work. Interesting is the constructive aspect dealt with in his essay: the classifications of the masonry vaults are related to the typical aspects of the local building traditions (e.g. *volte leggiere* — tile vaults or plaster vaults).

3. Overview of baroque domes in Naples

Numerous studies carried out on the topic show that it is possible to count approximately 80 domes in Naples in the urban area extending on the north-south side from Capodimonte to the sea and on the east-west side from the business center to Mergellina (Baculo Giusti, 1999). The presence of so many domes, starting from the Renaissance treatises in the Neapolitan scenario, is evidence of the sacred history of the city. The practice of religious orders to delineate a space, an island, within the structure of the historical city can be noted, when over years the domes become the indicator of their presence in the territory. It is enough to take a look at the view of Naples by F. B. Werner and H. J. Wolff dating back to the beginning of the 18th century (Figure 3) and the 18th century topographic map by the Duke of Noja Giovanni Carafa (Figure 4) to appreciate the number of domes in the city.

Figure 3. Striking large-format view of Naples, showing the town from the harbor. This is the second (of three) editions. The first includes the name Jerimiah Wolff. The credit indicates that the view was newly engraved by F. B. Werner. Photo: Barry Lawrence Ruderman. Antique Maps Inc.

DOI: 10.23968/2500-0055-2020-5-2-08-16

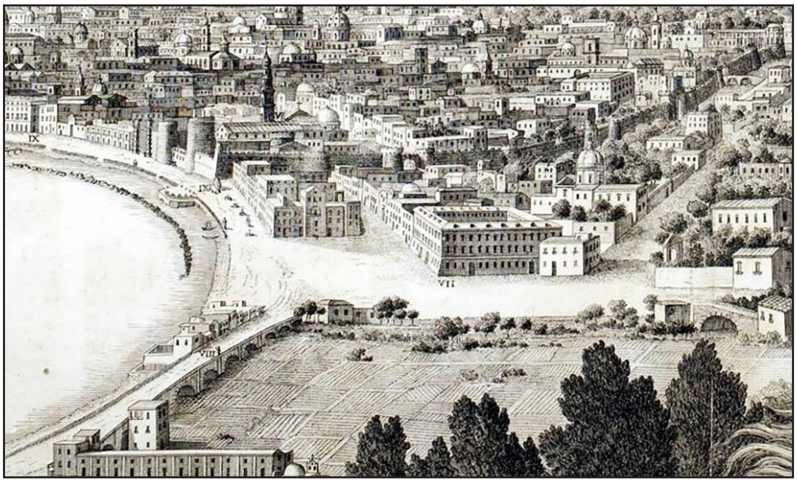

Figure 4. Giovanni Carafa Duke of Noja (1775). *Mappa topografica della città e de' suoi contorni.* Details of Tav. 27 in which the domes of the eastern part of the city can be identified.

The Neapolitan 17th century is characterized by disastrous episodes such as the earthquakes that occurred in 1627, 1688, and 1694. The two earthquakes of 1688 and 1694 caused significant damage to the architectural heritage, which was already in precarious static conditions. As a consequence, numerous consolidation works were undertaken, which often also made formal changes to the monuments. Without any doubt, it can be said that the greatest number of restorations of churches can be attributed precisely to the 17th century, including the construction of the presbytery, transept and, above all, the addition of the dome as a structural element (Casiello, 2005).

Figure 5 shows the location in plan of the domes surveyed in Naples (Baculo Giusti, 1999), and, among all of them, the domes dating back to the Baroque period, which contributed to defining the context of the ancient Neapolitan center, are highlighted in rectangles.

Figure 5. Map of the city of Naples: graphic elaboration by A. Scorpinti (Baculo Giusti, 1999). The image shows the location in plan of the surveyed domes; underlined by the authors are the baroque domes.

3.1 Structure

The study of Neapolitan Baroque domes started from a systematic collection of documents concerning previous studies. The information therein was then classified according to geometric, constructive and mechanical aspects.

3.1.1 Dome geometry

As known, geometry is the main aspect that comes into play when analyzing a historic masonry structure. From the first reading, it is possible to deduce that most of the domes detected are circular in plan, extradosed and have a simple shell. Among them, we distinguish:

- domes without a lantern, with a drum (raised-arch dome, rounded-arch dome) such as St. Maria della Colonna (Figure 6a);
- domes without a lantern, without a drum (lowered-arch dome) such as SS. Trinità dei Pellegrini (Figure 6b);
- domes with a lantern, with a drum (raised-arch dome, rounded-arch dome, lowered-arch dome) as the case of SS. Annunziata (Figure 6c);
- the only dome with a lantern and without a drum (lowered-arch dome) — St. Angelo a Nilo (Figure 6d).

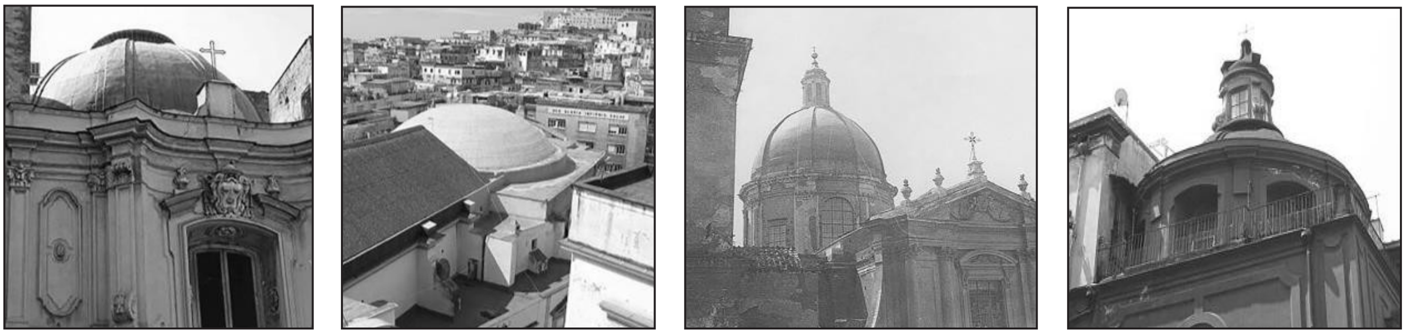
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Figure 6. (a) The dome of St. Maria della Colonna without a lantern, with a drum; (b) the dome of SS. Trinità dei Pellegrini without a lantern, without a drum; (c) the dome of SS. Annunziata with a lantern, with a drum; (d) the dome of St. Angelo a Nilo with a lantern and without a drum (Casiello, 2005).

In a smaller number, but still present, are the domes that are circular in plan, with a double shell, extradosed, with a lantern (with or without a drum) (Figure 7a). There is no shortage of elliptical domes, all of which consist of a simple shell, are extradosed and with a lantern (with or without a drum) (Figures 7b and 7c).

Figure 8 provides a diagram summarizing the first classification of the surveyed domes according to the major geometrical and typological parameters.

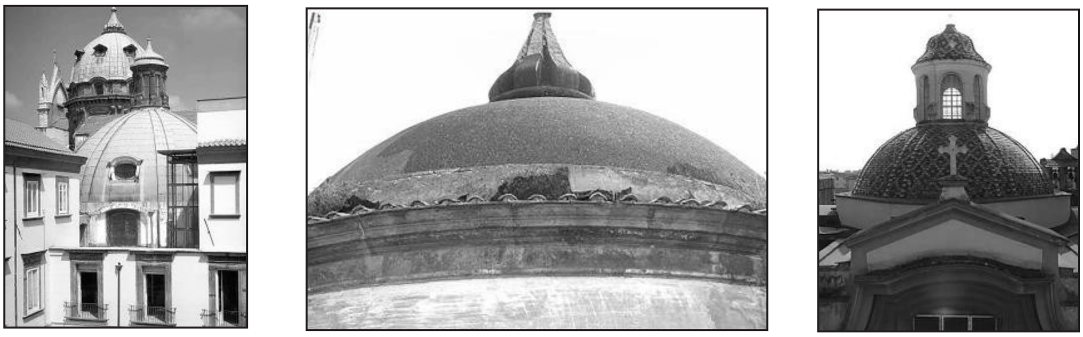
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Figure 7. (a) The dome of Pio Monte della Misericordia with a lantern, with a drum; (b) the dome of SS. Trinità dei Pellegrini with a lantern, with a drum; (c) the dome of St. Maria del Popolo agli Incurabili with a lantern, with a drum (Casiello, 2005).

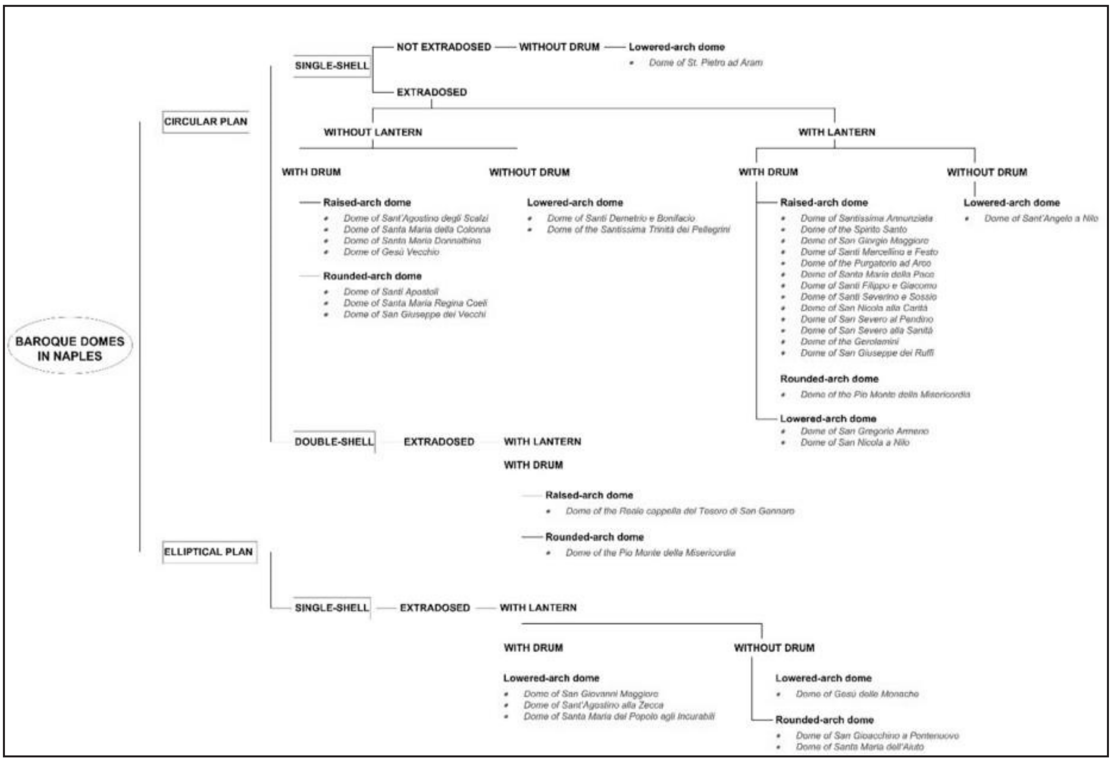
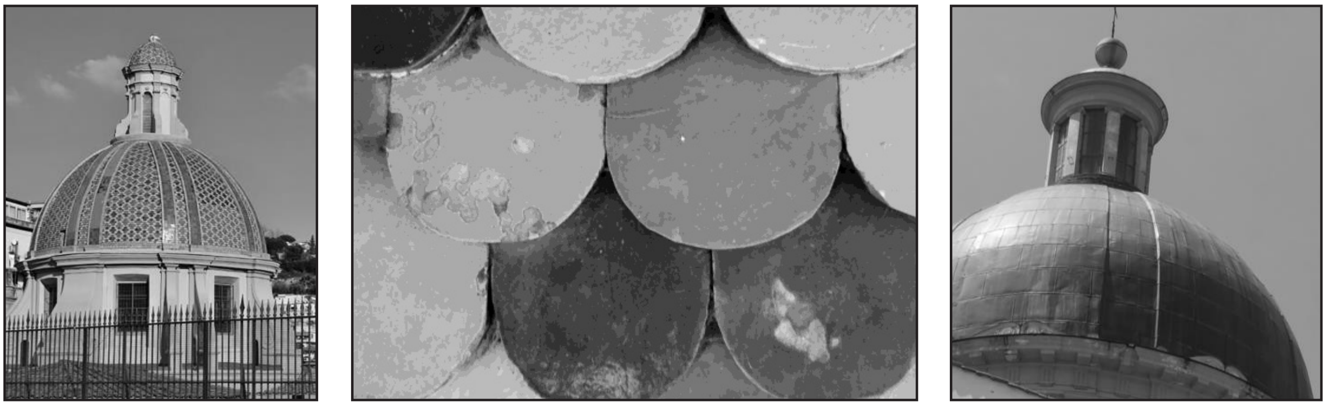


Figure 8. Classification of the surveyed domes according to the major geometrical and typological parameters (diagram by the authors). It also shows a list of the domes, with their names, organized by categories.

3.1.2. Construction features

The second classification of baroque domes may refer to the materials and construction techniques used for their realization. The Neapolitan building tradition of the period between the 17^{th} and 18^{th} centuries includes the widespread use of cutting stone and stone chipped (*a scheggione*) as well as domes made by concretion and ribbed (Renzullo, 1999). Tuff or Vesuvian stones were the main materials used. The tuff ashlars were worked in the form of wedges and connected by mortar joints; the Vesuvian stones, much more regular, allowed a perfectly fitting laying surface that did not require mortar, except for a small surface cover during placement. Due to the great availability of stones in the form of chips, domes of limited size could be built. Concrete domes, on the other hand, derive from a tradition dating back to the Romans. This construction technique did not involve the use of stone ashlars but a conglomerate of lime mortar and *pozzolana* together with tuff or volcanic stone chips. Subsequently, this method was improved with the introduction of meridian ribs as well as discharge arches along the parallels. The baroque aspect of the Neapolitan domes can be clearly seen in the exterior (Penta, 1999). In fact, it was customary to cover the extrados of the dome with polychrome majolica, a formal solution of oriental influence (Arabic art).

The distribution of the majolica tiles was attributed to architect Giuseppe Donzelli, known as Fra' Nuvolo (Figure 9a). This covering was made by means of majolica tiles arranged according to crossed diagonals to form a grid. The fixing of these roof tiles was provided by spikes and mortar. Since the 1600s, it was typical to use copper and lead coating, which also helped to ensure protection against corrosion due to atmospheric agents (Renzullo, 1999). Among the most significant examples of lead covering, we can mention the dome of Girolamini (Figure 9b) and Sant'Agostino agli Scalzi.



a b c

Figure 9. (a) The dome of St. Maria della Sanità in Naples; (b) details of majolica roof tiles; (c) the dome of Girolamini in Naples. Photo by José Maria Gonzales Spinola in Vesuvioweb, October 11, 2013.

3.1.3. Stability (masonry mechanics)

One of the most important factors that concern numerical modeling of masonry structures is the estimation of mechanical properties of the material; on the other hand, the characterization of the geometry of these types of construction typologies is a significant problem (Cennamo et al., 2017a). In order to know the mechanical behavior of these structural elements, reference is made to the Modern Limit Analysis Theory applied to masonry structures, to assess their degree of safety and interpret the changes they have undergone (Cennamo et al., 2017b).

As known, masonry constructions are built with a material that satisfies three conditions. Firstly, the tensile strength in masonry is zero; in particular, the mortar joints in masonry have no tensile strength: this is in favor of safety considering that there is always a certain adherence to the mortar. Secondly, the masonry material works in compression: the tensions are so low that the compressive strength can be considered as infinite; thus, material strength properties are not of concern. Finally, a sliding failure cannot occur. Under these conditions, the material complies with standards and the fundamental principles of limit analysis can be observed for masonry (Cennamo et al., 2018a; Heyman, 1995). Within the framework of Limit Analysis, the fundamental Safe Theorem states that if any equilibrium state can be found, for which the structure is purely compressed, then the structure is stable, so a collapse can never occur under the given loads (Huerta, 2004). For stable masonry structures, there are infinitely many states of equilibrium that do not violate the hypotheses for the material. Some of them can be represented either by a family of lines of thrust (Cennamo et al., 2019; Cusano et al., 2018) or by membrane stress states (Cennamo et al., 2018b; Cennamo et al., 2018). Many authors (Cennamo and Cusano, 2018; Cennamo et al., 2017) refer to the application of limit analysis to arches, vaults, and domes.

4. Discussion

As already mentioned above, this article presents a research work in progress. The current state concerning the topic of the Neapolitan Baroque domes has been retraced as a starting point for future studies on historical heritage preservation. No one has ever claimed to exhaust the complexity of such a quantitatively varied and significant casuistry.

The aim was rather to underline what a lack of knowledge of such elements' values can produce, on the one hand, and, on the other hand, to implement a multidisciplinary program providing a solid background when it is necessary to intervene on these historical artefacts. Even the issue of mechanics, which has always been neglected in the studies conducted so far, is a key factor for the authors to understand how these constructions were conceived by engineers and architects of the past. From this point of view, structural treatises may provide useful information about the knowledge acquired by ancient builders in order to plan their structures. For good restoration work, it is absolutely indispensable to deeply investigate the geometrical and constructive aspects of a building, as well as its mechanical properties, in order to avoid approaches and methods of structural analyses far from the real behavior of these masonrystructures.

It is necessary to point out that the static history of any ancient construction should be particularly attentive to less conspicuous aspects and should make use of archival and bibliographical sources to obtain useful information about materials provenance, construction techniques and consolidation methods. The interrelationship between in-situ inspections and historical investigations may help to choose specific solutions to be adopted (De Martino and Russo, 2005).

5. Conclusions and future works

The architecture of the 16th and 17th centuries in Naples shows remarkable features that arise directly from the building techniques used for the construction of vaults and domes. Starting from the state of the art, from the list of the domes surveyed in the Neapolitan area and their planimetric location, the objectives of the future research works are manifold.

Firstly, it seems necessary to conduct the archival and bibliographic research for those domes, of which there is little (or no) information for the reconstruction of the building stages of the artefact. For the domes already extensively documented from a historic point of view, the useful information shall be duly selected to define a complete framework on the constructive techniques adopted to build them. The investigation also aims to compare different domes belonging to the same historical period in Naples (and not).

As known, the geometrical surveys and laser scanning for those domes, of which there is no information yet, as well as the study of the geometry, dimensional aspects, and typology are a part of the complete knowledge of the building. Thus, the ultimate goal is to conduct a study on the stability of the domes, applying limit analysis combined with the graphic statics, bearing in mind that the methods used today to analyze masonry structures, based on FEM and elastic theory, are not suitable for these kinds of structures, for which only the geometry (stability) needs to be controlled in the analysis process.

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DOI: 10.23968/2500-0055-2020-5-2-17-24

RESTORED LAYERS: RECONSTRUCTION OF HISTORICAL SITES AND RESTORATION OF ARCHITECTURAL HERITAGE: THE EXPERIENCE OF THE UNITED STATES AND RUSSIA (CASE STUDY OF ST. PETERSBURG)

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Abstract

Introduction: The need for maintenance and repair of historical buildings is an important and integral part of the preservation of cultural and architectural heritage. **Purpose of the study:** The study is aimed to find common-ground potential project concepts in the intersection of the new and old in the sacred and the mundane. **Methods:** The authors perform a theoretical analysis of techniques for restoration of recognized monuments, such as the Hermitage, and ordinary historical objects, and determine a relationship between the concept and the problems of restoration. To demonstrate methods used in restoration, the authors offer specific examples from modern practice in the United States and Russia. **Results:** The article discusses cases where professionals do not attempt to return buildings to some idealized version from the past, but rather use the restoration process to emphasize the qualities of age, show how they exist in the present, and recognize the built environment as alive, evolving, and constantly changing. The article reflects the work of the authors, including projects from their architectural practice and teaching. **Discussion:** With regard to the implementation of specific restoration and reconstruction projects, the importance of international interaction is shown in the development of strategies for education and practice in the field of restoration and protection of cultural heritage. The increasing volume of conservation and restoration work puts pressure on developing scientific approaches and methodologies to solve practical problems. At the same time, the restorer must recognize that continuity with the past can exist in the renovation of more mundane and utilitarian structures, which can benefit from less restrictive approaches with regard to the intersection of the old and the new. After all, a trained professional should understand that the approach to each project is unique.

Keywords

Architectural heritage, restoration, adaptation, innovation, historical building structures, Russian and American experience.

Introduction

International cooperation and development of strategies for education and practice in the field of cultural heritage restoration and conservation require analyzing both the Russian and international experience in the creation and operation of historical sites and structures. Preservation of architectural monuments periodically involves theoretically substantiated conservation and restoration works. Techniques of conservation and restoration applied are fluid and require every restorer to take a creative approach to address issues specific to a given project.

Decay is a fundamental and unavoidable component of the built environment, documenting the passage of time and “stirring our memories and imaginations” (Jurow, 1978). As noted scholar David Lowenthal points out, “buildings are expected to gain through the process of growing old, it is part of the quality we admire in them that they have their history written on their faces” (Lowenthal, 1985). Sociologist Yi-Fu Tuan notes that a sense of age embodied within the architecture of a given community creates a sense of “time depth” and “roots” us to a place, generating a sense of personal attachment (Tuan, 1974). Conservation strategies can both preserve and encourage depth and continuity, recognizing architecture as something alive and evolving.

When determining the appropriate restoration technique of a public facility, of critical importance is the assessment of its historical and architectural value. Facilities deemed to have less historic significance may offer the designer greater license to creatively engage the existing condition and celebrate the intersection of new and old. Reconstruction may be decided upon only in a case when the architectural value of the facility is not high, or when a historical structure is in an advanced state of dilapidation requiring immediate intervention to preserve and prolong the life of the monument. Reconstruction is also possible when the monument's utility system needs to be replaced in accordance with the modern requirements of the constantly developing city. The Russian experience of restoration can be considered through the lens of some of the outstanding monuments in St. Petersburg, many of which are under UNESCO protection. To determine the technical condition of the building, it is necessary to have information about its actual structural strength, rigidity, the presence and location of rigid connections, homogeneity, material density, etc. (Lysova and Sharlygina, 1979).

1. Methods

The Federal Law "On Objects of Cultural Heritage of the Russian Federation" in Chapter 7 prescribes a number of concepts that define possible measures to be taken within the framework of preserving the object of cultural heritage: conservation (Article 41), repairing of the monument (Article 42), restoration (Article 43), adaptation of the object of cultural heritage for modern use (Article 44), etc. (Federal Law as of 25.06.2002). Restoration and adaptation are assumed to be the most relevant measures at present. The concept of "reconstruction" is not included into the Federal Law, but the Urban Planning Code of the Russian Federation (Clause 14) in a situation where there are few objects of protection on the site, allows some specific activities to be undertaken (Urban Planning Code of the Russian Federation as of 29.12.2004). Besides, sub-clauses 14.1−14.3 provide additional necessary clarifications in the definitions.

The entire historical center of Saint Petersburg and monument complexes related to it have been included in the UNESCO World Heritage List since 1990. In this regard, it seems extremely important to preserve, repurpose and adapt the cultural heritage objects of the city for modern use, as well as to identify and register new monuments of history, culture and architecture.

In recent years, innovative technologies have been actively introduced and new methods have been applied in restoration and adaptation of cultural heritage sites in St. Petersburg to the modern needs of society. Over the past decades, many cultural heritage sites in St. Petersburg have been reconstructed (with varying success), among them the General Staff Building, the Senate Building, the Central Museum of Communications, the DLT, the Passage, the Kamennoostrovsky Theater, and the Kamennoostrovsky Palace. We will also consider examples from abroad, modest in scale but important to provide a frame to evaluate a preservation strategy, such as the work of David Ireland in San Francisco and modifications to historic manufacturing facilities if the same region.

2. Results

2.1. Architectural Heritage Sites of Saint Petersburg

2.1.1. Kamennoostrovsky Theater, St. Petersburg

Basing on the legislative framework of the Russian Federation in the issue of preservation of architectural monuments, the authors believe that it is possible to correctly combine constructional measures and classical restoration of the monument. The complex of works carried out on the monument of history and culture of the XIX century, namely, the Kamennoostrovsky Theater, which afterwards started to be used as the second stage of the Tovstonogov Bolshoi Drama Theater (BDT), may be regarded as one of the most striking examples of the synthesis of art and engineering.

The Kamennoostrovsky Theater is a unique monument of classical wooden architecture in St. Petersburg, designed by architect S. L. Shustov (1827). The theater is recognized as an object of cultural heritage of the Russian Federation (Figure 1).

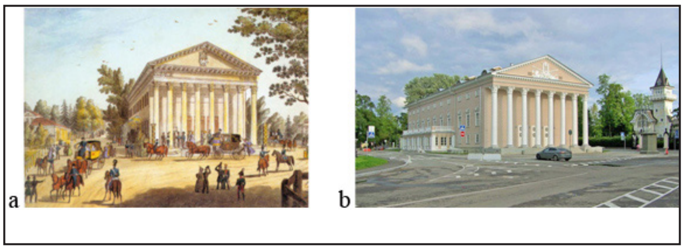

Figure 1. General view of the Kamennoostrovsky Theater: a — a view of the Kamennoostrovsky Theater in the 19th century, a reproduction from the Russian Artistic Journal, Saint Petersburg, 1853, No. 20; b — a 3D model of the modernized Kamennoostrovsky Theater, built by specialists of Georeconstruction company (Dementieva et al., 2014).

In 2007, as assigned by the KGIOP (Government Committee for Historical and Cultural Heritage Management), architect V. Burygin developed the concept of theater adaptation, with the construction of an underground garage under the building and the area around it. The architect envisioned the restoration of the wooden building without disassembling it, recreating the historic interiors. Based on this concept, the adaptation of the Kamennoostrovsky Theater was developed and implemented. The project was awarded the gold medal "For outstanding achievements in the field of heritage protection in Europe" at the international exhibition for the protection of monuments "Denkmal" held in Leipzig (Germany) in 2010 under the auspices of UNESCO. The theater was adapted for year-round use and retrofitted with technologically advanced theater equipment while maintaining and preserving the authenticity of the monument. This was made possible by implementing state-of-the-art techniques in the fields of restoration engineering and geotechnical engineering (Handel, 2013).

A unique feature of this project was the development of the underground space in complex engineering and geological conditions of St. Petersburg, with weak clay soils taken into account. St. Petersburg specialists in geotechnical engineering had to develop their structural assessment programs (based on research and data compiled over the course of twenty years), which enabled them to solve complicated foundation conditions. The engineers created a viscoplastic model of the soil simulating the behavior features of water-saturated clay soils. The architects did their best to follow the principle of avoiding any possible harm to the monument when developing the underground space

DOI: 10.23968/2500-0055-2020-5-2-17-24

under the Kamennoostrovsky Theater, and, accordingly, selected a proper design solution. Based on the research performed, special requirements were developed for the design of deep pits near architectural monuments: analysis of underground structures in urban development had to be carried out for both the project structure itself and for the surrounding housing development. An underpinning was carried out by piling of the historical structures: the historical basement was encircled with a reinforced concrete binding belt, and bored piles were placed along its sides. The load of the building was then transferred onto them using metal beams placed in the windows under the binding belt. The historic wooden piles of the theater ended up between the new underpinning piles. The design of the land cofferdam ensured the preservation of the natural level of groundwater. Meticulous monitoring during the entire period of construction work made it possible to avoid any dynamic effects that exceeded the permissible level of vibration acceleration (0.15 m/s^2) (Figure 2) (Dementieva et al., 2014).

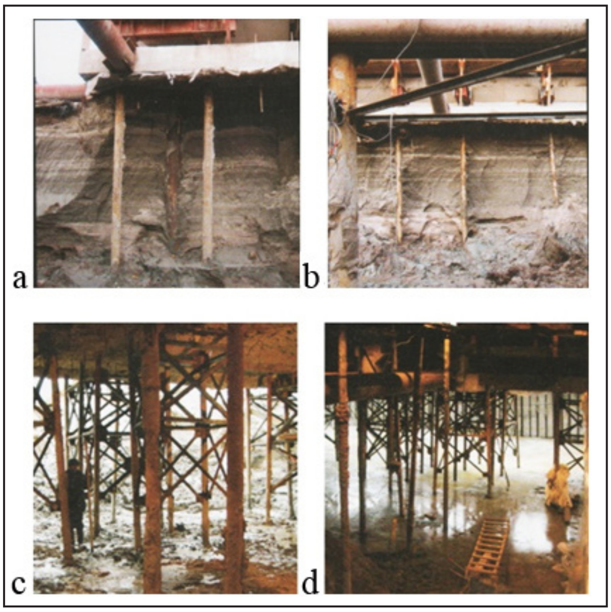

Figure 2. Work on the construction of the underground space under the theater: a, b — excavation of the underground space; c, d — historical wooden piles between new underpinning piles. Photos made by employees of Georeconstruction company, scan copies from the book “About the Kamennoostrovsky Theater” (Dementieva et al., 2014).

2.1.2. Museum complex of the State Hermitage Museum, St. Petersburg

During the preparation for the 250th Anniversary of the Hermitage Museum (in 2014), there was a large-scale survey of the Hermitage in the broadest sense: as an architectural complex, as the world and national Museum, as a keeper of the heritage of times and antiquities, as a collector of new and unique exhibits, as an organizer of exhibitions at the highest international level. Restoration and reconstruction of the State Hermitage Museum complex in the Eastern wing of the General Staff Building (the project by N. I. Yavein’s Studio 44, 2002−2010) is a unique example of adapting a historical monument to the modern needs of society (Figure 3).

Figure 3. Interiors of the General Staff Building. Photos by the authors (Golovina S. G., 2018).

With the direct participation of foreign experts such as Dutch architect Rem Koolhaas and architectural design studio AMO, the following areas were restored: the attic premises of the Winter Palace, the premises of the Small Hermitage, the new utility rooms equipped with the newest engineering systems for reception and storage of unique museum exhibits, the underground passage between the buildings of the complex (Farahat and Osman, 2018). This was in immediate proximity from the Neva River (less than 6 meters). Despite the fact that the result of the bulk of the work is hidden from view, all activities that were undertaken in both the architectural restoration and the engineering works are of great importance for the proper functioning and introduction of modern equipment to the Museum complex. Some of the latest technologies used in the newly renovated premises can already be appreciated by visitors, e.g. backlit information panels on the walls have replaced the usual signs with text (Figure 4).

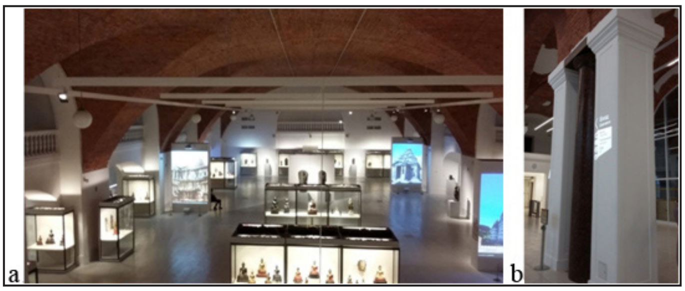

Figure 4. New exhibition spaces in the Small Hermitage: a — a hall with an exposition; b — backlit panels. Photos by the authors (Pastukh O. A., 2016).

Especially noteworthy is the process of reconstruction of the Hermitage’s attic space.

Unlike the halls of the Hermitage with their lavish decoration, the attic premises have a very special atmosphere. This is really an unusual space, its architecture is inextricably linked with the architecture of the halls located below (Matsenkov, 2011). The attics of the Hermitage can be understood through the transition of material, from wood (before the beginning of the XIX century) to metal (early XIX century). Initially, almost all the buildings of the Hermitage had a wooden rafter system, but after the fire of 1837, the Winter Palace "provided itself" with iron structures. In 1887, the trussed rafters of the Winter Palace were reconstructed. In 1914, a new system of air heating and ventilation was built in the Small, Old and New Hermitage buildings, which some researchers consider to be the world's first air conditioning system created in a museum (Matsenkov, 2011). During the Great Patriotic War, the "front line of defense" of the Hermitage against German invaders was located through the roofs and attics. One of the shells of an anti-aircraft gun of 1939 vintage was found in the sand of the attic above the Tent-Roofed Hall during repair works in 2000. Now, nine separate places show traces of shell damage in the attics of the Winter Palace and the Hermitage — shrapnel wounds on brick walls and deformed iron structures with seams from electric welding. Currently, the attics of the Winter Palace, the Small Hermitage, and the Hermitage Theater contain elevator machinery and air conditioning equipment. In recent years, the attics of the Hermitage have attracted a lot of attention. In 2001, an elevator was installed to get to the attic above the Commandant Entrance of the Winter Palace. The Hermitage attics have an aesthetic component in addition to quite utilitarian functions (the location of the rafter system and the ventilation system). They are beautiful in their own way with their "brick-and-iron" interiors and arouse keen interest of the visitors, opening up another dimension to them (Figure 5).

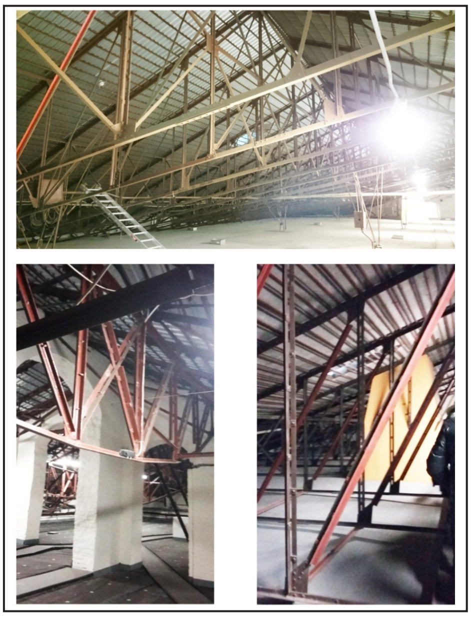

Figure 5. Attic premises of the Hermitage after restoration in 2000. Photos by the authors (Pastukh O. A., a guided tour for the faculty of the Department of Architectural and Engineering Constructions, 2016)

A careful and respectful attitude toward historical structures is the key to the harmonious existence of the past and present. For the preservation of the historical, cultural and urban heritage of St. Petersburg, it is extremely important to implement a radically new approach to the reconstruction of the city center; one which uses "sparing" methods of repair work, is equipped with innovative and advanced technologies and is the most productive use of the limited opportunities for restoration (Pastukh, 2016).

2.2. Renovation of historical sites in the USA

2.2.1. 500 Capp Street, San Francisco, California

Artist Jim Dine, who works the surfaces of his pastel drawings with sandpaper and gesso to alter but not erase, builds up his drawings and expresses the process of making, the drawing's history, in the finished product (Figure 6). As Dine explains, "overlay and rubbing out come not so much from frustration at what I'm getting as from the confidence that I am going to do it again… and I know I am going to get something richer than if I had left it alone" (Glenn, 1979). The drawing in this case benefits from layering and depth, celebrating and revealing the messiness of the process. We can extend this sensibility to architecture, designers empowered by confidence that restoration will become richer and gain depth through the creative engagement of the existing condition.

Figure 6. Jim Dine, figure drawing, 1977. Photos by Timothy Gray.

Artist and architect David Ireland brings this same sensibility to architectural restoration, where he treats the restoration of the ordinary with the same reverence and intensity of investigation that an archeologist might bring to a historical dig. In his first built work, 500 Capp Street, the restoration of the artist's own home and studio, Ireland interrogated a historic single-family home located in San Francisco's Mission District as he methodically peeled back the layers of time and emptied years of debris which had accumulated in the house (Figure 7). Rather than trying to restore the home to some idealized version of the past, Ireland's renovation celebrated and revealed the building's history while at the same time making the space functional and whole. "Ireland's goal was not to improve or remodel 500 Capp Street, but, rather, to uncover its history as an artifact molded by human use and the passage of time" (Tsujimoto and Gross, 2003).

Ireland peeled back layers of old wallpaper to reveal plaster and layers of paint, trims removed, floors cleaned

DOI: 10.23968/2500-0055-2020-5-2-17-24

and oiled. As the contents were emptied, artifacts that caught the artist's eye were removed and cataloged from the stream of debris. These items were then reconfigured and introduced back into the finished space as sculptural installations. Guided by his intuition — the process was arrested at a certain point — Ireland intentionally preserved "stress cracks, water stains and other signs of aging" (Tsujimoto and Gross, 2003) and sealed the walls, ceilings and floors with thick coats of a gloss lacquer. The building was restored to a clean and usable state but celebrated its age and the passage of time by wearing its history on its face.

Figure 7. 500 Capp Street, David Ireland. Photos by Timothy Gray.

2.2.2. Headlands Center for the Arts, Marin, California

In the Headlands Center for the Arts, located just across the Golden Gate Bridge from San Francisco, Ireland and a team of collaborators embraced the same approach in the conversion of a decommissioned army barracks into a center for artists in residency. Layers of paint are peeled back, walls cleaned and sealed. Furniture systems in the main meeting room, designed by architect Marc Mack, are simultaneously inspired by but distinct from the existing space. The circular geometry of the seating system is set in opposition to the orthogonal regularity of the base building, celebrating and amplifying the unique quality of the base condition through the contrast of material and form (Figure 8).

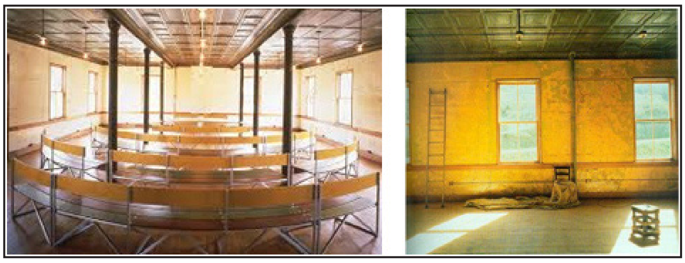

Figure 8. Headlands Center for the Arts, Marin, California, David Ireland, Marc Mack. Photos by Timothy Gray.

2.2.3. Offices for Vehicle Design, San Francisco

Inspired by this approach in his own work, both professionally and with students, the author has creatively engaged historic building conditions in similar ways. In the offices for Vehicle Design, San Francisco, a historic post and timber manufacturing facility was converted into offices for the advertising Agency Vehicle Design. As part of the renovation, the three-story unreinforced masonry building had to be brought into compliance with current seismic code. Massive steel moment frames were craned through the roof of the existing building, and the masonry perimeter walls were strapped to the heavy timber frame. The structural reinforcement was not concealed but rather celebrated and allowed to have a strong presence in the finished space (Figure 9).

Existing machinery from the building's past life as a manufacturing facility was removed from the space, leaving voids where the fir flooring had been cut around the machinery mounts. Rather than patching or trying to conceal these imperfections, a cement leveling agent was poured into the voids left by the machinery, making the floor safe and functional but recording and revealing the past use of the building, a layer of time celebrated rather than concealed. New items, such as the conference room at the entry to the space, were constructed using a delicate material palette of aluminum and glass, celebrating the rugged quality of both the new seismic framing and the existing post and timber frame through contrast. The rugged beauty of the timber frame is amplified by the juxtaposition with the material system of glass and aluminum. The inherent beauty of the historic base building condition is celebrated through the contrast of materials and scale. Similar to the Headlands Center for the Arts, custom-designed furniture for the space is inspired by the past but is distinct of the present. Material selections are inspired by the base building but are assembled using clean, crisp lines distinct from the rugged beauty of the base building condition.

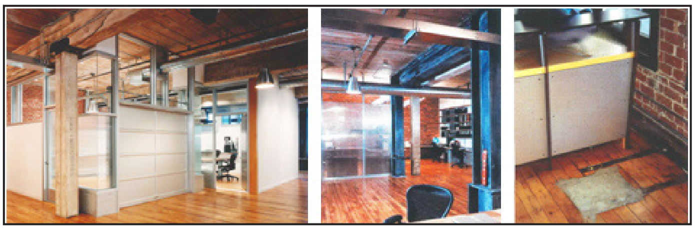

Figure 9. Offices for Vehicle Design, San Francisco, Gray Architecture, reception desk details, conference rooms and a seismic frame. Photos by Timothy Gray.

3. Discussion

Preservation of architectural heritage is a topic that not only attracts increased public attention but is also discussed by professionals in a lively, fierce debate. The interests of residents, officials, architects, representatives of business communities, and investors, as well as large construction companies have converged on the question of how and why to preserve monuments (Pastukh et al., 2019). There are a number of pressing problems in the field of monument protection, the answers to which will help to find a consensus in all the variety of professional opinions related to this topic:

1. Why do we need to preserve our heritage? What role should the concept of authenticity play? When is it appropriate to restore lost monuments?
2. Does the government have all the tools to effectively perform the task of protecting the heritage?
3. How can laws in the field of heritage protection and their practical application be evaluated?
4. What is the state of the Russian restoration branch?

As answers to these questions, it is interesting to hear the opinions of well-known practitioners in the field of preserving the historical urban environment and individual monuments, depending on the specifics of their activities and experience in this field.

Architect Rem Koolhaas: "Conservation"

It should not be about authenticity or architecture as such, but about preserving visible traces of history — so that they would be accessible and understandable unconditionally — not only some good or significant places but also everyday life as well. Designers have a widely spread delusion that it is possible to solve complex cultural and political problems basing on the economy. On the one hand, having embarked on the path of market economy development, Russia very quickly became a victim, especially in large cities, of the same mechanisms of conservation economy as in the rest of the capitalist world. On the other hand, in the Soviet Union, there were many cases of involuntary preservation, when, for example, parts of cities or even regions were either dropped from the field of Soviet planning or frozen by some political reasons. Something similar can be observed today. After the collapse of the USSR, Russia lost much of its coherence. Many airports were closed in small and medium-sized cities. The lack of infrastructure hinders the processes that are associated with the interests generated by the market economy, contributing to the preservation of not only Soviet but even pre-Soviet realities.

Architect Timothy Gray:

Having practiced for many years in San Francisco, a city subject to extensive codes and ordinances governing the preservation of the city's historic fabric, I can tell you that building owners were typically very reluctant to own or purchase properties listed on the historic register due to the strict limitations and oversight on development. Abundant regulation can limit the economic potential of a given property as well as the potential for creative design solutions. Some of the best and most creative work emerges from the intersection of the new and the old in buildings that embody richness and history but are not deemed historically significant.

Architect Nikita Yavein: "It is almost impossible to recreate monuments":

The process that I observe is not progressing, but is very ragged, jerky, with different speeds, and periodically there are tides of aggressive unprofessionalism. Today, the pendulum swung very far in the defensive direction. On the one hand, the legislation is being tightened. On the other hand, in practice, there is still a very strong wave of aggression against a number of monuments. The legislation is more or less formed. Now more and more investors are working with monuments, who do not want to reckon with the laws. Sometimes there are very strange ideas, for example, a project for UNESCO, where the area of the St. Petersburg security zone is proposed to be 300 square kilometers, which is more than all the security zones in Europe combined. In fact, we have to deal with the remnants of legislation. For example, the law excluded the concept of "reconstruction" and introduced the concept of "adaptation", which is fundamentally inconsistent with the Urban Planning Code. That is, the law is still somewhat detached from reality. In world architectural practice, there is a concept of "special technical condition", when each unique object actually creates its own legislation. The special technical condition is approved accordingly and then acts as a normative act. A historical building and its modern contents are usually absolutely incomparable in value. With this approach, you need to follow the rules of the game very clearly, separating the new from the old, without using any styling. This interpretation of the Venice Charter in 90 cases out of 100 turns out to be parasitic on the old one. Although the possibilities of such a contrast are more often used by Western masters.

Conclusions

With regard to the implementation of specific restoration and reconstruction projects, the importance of international interaction was shown in the development of strategies for education and practice in the field of restoration and protection of cultural heritage. The increasing volume of conservation and restoration work puts pressure on developing scientific approaches and methodologies to solve practical problems. Consequently, engineering conservation of architectural monuments requires close attention and collaboration of various specialists, primarily architects, restorers, engineers, and archaeologists.

Preservation of historical and cultural monuments is the main task of engineering conservation and restoration. As the analysis of the Russian experience in the field of restoration and reconstruction shows, along with outstanding examples of engineering and architectural thought, there are, to put it mildly, some unsuccessful ones (Pastukh et al., 2018). Each monument possesses individual features that are intrinsic to it, and therefore they have a special value. This is why it is unacceptable to destroy these individual features during restoration. All work should be mechanized as much as possible. This will increase productivity and reduce costs. Methods of production should be constantly improved and thus reduce the labor intensity.

A lot has been done in Russia to preserve the cultural heritage of the past, including monuments of architecture, culture and history. The possibilities of modern construction equipment are practically unlimited. Currently, it is possible to straighten, restore, preserve, lift, move, and save any monument, even in an emergency state, without changing its appearance. Architectural monuments themselves are often the creations of great artists who have invested their skills in them. This means that the restorer renovating the monument does not have the right to change the master's plan and, most importantly, should not miss when restoring what was accurately determined by the remaining traces. At the same time, the restorer must recognize that continuity with the past can exist in the renovation of more mundane and utilitarian structures, which can benefit from less restrictive approaches with regard to the intersections of the old and the new. After all, a trained professional should understand that the approach to each project is unique.

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ВОССТАНОВЛЕННЫЕ СЛОИ: РЕКОНСТРУКЦИЯ ИСТОРИЧЕСКИХ ОБЪЕКТОВ И ВОССТАНОВЛЕНИЕ АРХИТЕКТУРНОГО НАСЛЕДИЯ: ОПЫТ СОЕДИНЕННЫХ ШТАТОВ АМЕРИКИ И РОССИИ (НА ПРИМЕРЕ САНКТ-ПЕТЕРБУРГА)

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Аннотация

Необходимость технического обслуживания и ремонта исторических зданий является важной и неотъемлемой частью сохранения культурного и архитектурного наследия. **Цель исследования.** Найти точки соприкосновения потенциальных проектных концепций на пересечении Нового строительства и наследия прошлого в сакральном и обывательском смысле. **Методы.** Теоретический анализ методов реставрации как известных памятников, таких как Эрмитаж, так и тривиальных исторических объектов, а также взаимосвязь между архитектурной концепцией и техническими проблемами реставрации здания. Для демонстрации этих методов реставрации авторы приводят конкретные примеры из современной практики в США и России. **Результаты.** Рассматриваются примеры, которые не пытаются вернуть здания к какой-то идеализированной версии из прошлого, а скорее используют процесс реставрации, чтобы подчеркнуть достоинства сохранившегося образца, как он есть, показать, как он есть, и признать созданную историческую среду живой, развивающейся и постоянно меняющейся. В статье отражена работа авторов, в том числе над проектами из собственной архитектурной практики и преподавания. **Обсуждение** реализации конкретных проектов реставрации и реконструкции показало важность международного сотрудничества в разработке образовательных стратегий и практик в области реставрации и охраны культурного наследия. Растущий объем природоохранных и реставрационных работ оказывает влияние на развитие научных подходов и методик решения практических задач. В то же время реставратор должен признать, что преемственность с прошлым может существовать при реконструкции более обыденных и утилитарных структур, которые могут извлечь пользу из менее ограниченных подходов к взаимодействию прошлого и современности. Ведь квалифицированный специалист должен понимать, что подход к каждому проекту уникален.

Ключевые слова

Архитектурное наследие, реставрация, адаптация, инновации, исторические строительные конструкции, российский и американский опыт.

DOI: 10.23968/2500-0055-2020-5-2-25-31

Civil Engineering

STRENGTH PROPERTIES OF TRUSS ELEMENTS MADE OF ENVIRONMENTALLY-FRIENDLY STRUCTURAL LUMBER

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Abstract

Introduction: Softwood lumber is widely used to manufacture load-bearing structures. However, the quality of round wood used to manufacture such lumber has been deteriorating lately. Round wood decreases in diameter and often has heart rot. The article looks into the possibility of manufacturing elements of load-bearing structures using beams made of round wood of small diameter that have not been previously used to manufacture structural materials for construction purposes. It is suggested to make beams of such round wood preserving the trunk structure to the maximum (heartwood beams). Due to the preservation of the annual growth ring pattern, such beams have better strength properties as compared to traditional structural lumber. **Purpose of the study:** The study is aimed to determine the strength properties of engineering structures' elements made of heartwood beams sawn from round wood of small diameter. **Methods:** The authors tested an experimental truss made of heartwood beams by means of incremental loading until destruction. **Results:** The strength properties of the truss elements made of heartwood beams sawn from round wood of small diameter were determined. There is a good fit between the calculated values of stress in the truss elements and the experimental data. The structure was damaged in the panel points connecting the compression strut with the elements of the tension and compression chords. The tension elements and their joints remained undisturbed. The experimental structure has a safety factor of 2. Compared to the design load, such a value shows that the experimental truss has the required bearing capacity and is robust. The findings confirm that the strength properties of heartwood beams match the requirements for elements of load-bearing structures. The strength properties of heartwood beams make it possible to use them to manufacture load-bearing structures.

Keywords

Load-bearing structures, strength properties of beams, annual growth ring pattern, experimental-truss testing.

Introduction

Resource-saving and green technologies of raw material processing in industrial production are the basis of the efficient economic development of any state. This also goes for the manufacturing process of wood load-bearing structures. Softwood lumber is used to manufacture elements of load-bearing structures. Structural lumber must have exact geometric shape and strength properties necessary for the manufacture of engineering structures. Lately, the environmental situation has deteriorated, which affects, inter alia, woodland. Heart rot occurs in trunks more and more often (Semenkova, 2002). Lumber used for elements of load-bearing structures must not have heart rot. That is why the process of cutting trunks with heart rot into wood assortments includes the removal of rotten trunk parts. Heart rot invades, first of all, the part of a trunk near the root system, and this part has the largest diameter. As a result, the average diameter of sawn lumber typically decreases. The amount of sawn lumber of a smaller diameter grows. The environmental advantages of wood as a structural material are apparent. However, it is slightly less advantageous in terms of strength properties, deflection, required sections, etc. (Karelskiy et al., 2015; Nekliudova et al., 2014). It is the reason why proper structural analysis for elements of wood engineering structures is so important (Horvath et al., 2010).

Saw logs with a diameter of 14–18 cm account for more than half of the total number of all round wood delivered to the saw mills in the northern part of European Russia (Vorontsov and Surovtseva, 2002). In the future, due to the reduced quality of the forest land allocated to wood production, the number of such saw logs will increase even more. Structural lumber is cut from logs with a diameter of more than 22 cm with the heart removed. Saw logs of small diameter are not used to manufacture elements of load-bearing structures. This is due to the fact that the lumber made of them has a small size and the heart in the middle of the cross-section remains. The existing regulatory documents do not allow for the heart in lumber used to manufacture elements of load-bearing structures. This is due to the fact that less strong wood is located near the medullary sheath. Therefore, the probability of contraction cracks is high and the areas located near the heart may have rot (Chubinskii et al., 2014; Wei et al., 2011).

Saw logs of small diameter are made of the top area of trunks. Finnish scientist Ylinen (Ylinen, 1952) developed the most complete mechanical theory of the tree trunk. He considers a coniferous tree trunk to be a complex reinforced layered structure of uniform strength capable of significant elastic deformations. The layered structure of the wood in the trunk implies that more flexible layers of spring wood alternate with summer wood, which is tougher. Such a trunk structure ensures high stability in case of vertical loads caused by the mass of the trunk and the crown. The top part of the tree trunk mainly has small healthy intergrown knots that reinforce the structure of wood, and the medullary sheath is characterized by a high degree of intergrowth with the surrounding wood.

We suggest making beams that use the cross-section of lumber to the maximum from round wood of small diameter. That is why it is expedient to make beams with a section of 100 x 100, 115 x 125 mm and 125 x 125 mm of round wood with a diameter of 14, 16 and 18 cm in the top, respectively. These beams preserve the tree trunk structure to the fullest. The majority of annual growth layers preserve the ring structure. The medullary sheath is near the cross-section center. These are so-called heartwood beams (Figure 1).

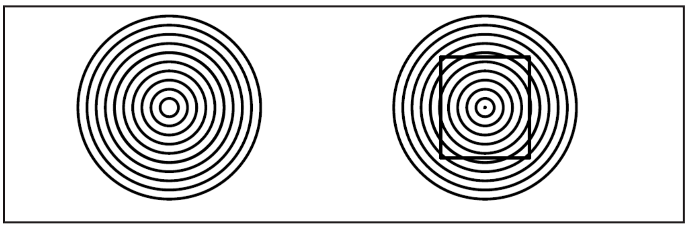

Figure 1. A diagram of manufacturing heartwood beams from round wood of small diameter.

Elements of load-bearing structures manufactured from heartwood beams operate under the conditions of transverse bending and compression along the wood grain with a bend. According to some studies (Byzov and Melekhov, 2011), the normal stresses occurring in such beams, having primarily a ring structure of annual growth layers, are 33–38% less than the normal stresses in traditional lumber.

The overview performed makes it possible to determine the purpose and tasks of the studies conducted. The purpose of this study is to determine the strength properties of engineering structures' elements made of heartwood beams sawn from round wood of small diameter. It requires solving the following tasks:

- Production of heartwood beams that have strength properties necessary to manufacture elements of load-bearing structures.
- Determination of the strength properties of the beams by testing the load-bearing structure made of such beams.

Methods

Pine heartwood beams with the cross-section sizes of 115 x 125 and 125 x 125 mm were sawn. The beams were dried until the moisture content of 18 ± 2%. Then, the beams were sorted visually into strength classes in accordance with the EN 338:2003 requirements. The beams obtained were of strength classes C24 and C14.

Various types of trusses are the most common load-bearing structures consisting of elements made of whole-section timber. Trusses with spans of 18 m are the most sought-after. In the course of the study, a truss with elements made of heartwood beams was tested. The truss structure has parallel chords and a triangular lattice (Figure 2).

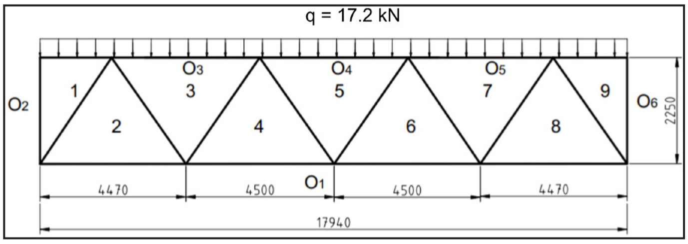

Figure 2. A diagram of the experimental engineering structure made of beam elements: O_1, O_2, O_3, O_4, O_5, O_6 are external areas defined by the structure contours and the lines of external forces; 1, 2, 3, 4, 5, 6, 7, 8, 9 are internal areas defined by the structure bars; q is a uniformly distributed load.

The truss elements undergoing deformation under transverse bending and compression along the grain are made of beams of relevant strength classes. The truss design load q is 17.2 kN/m. The structure height is 2580 mm. The width of the chords is as follows: the width of the upper chord — 423 mm, the width of the lower chord — 403 mm. The camber of the truss is 135 mm, the length of the chords is 18,420 mm. The structure is made of spruce beams of different sizes. The upper and lower chords of the structure are made of four beams. The length of the beams is 6140 mm. The upper compression chord is made of beams with a cross-section of 125 x 125 mm, the lower tension chord is made of beams of 115 x 125 mm, and beams of 125 x 125 mm are used for struts. Compression

DOI: 10.23968/2500-0055-2020-5-2-25-31

support struts consist of two beams with a cross-section of 125 x 125 mm. The moisture content of the beam wood was 12 ± 2% at the time of the testing.

We assessed the stress–strain state of the experimental structure consisting of beam elements made of beams manufactured from round wood assortments of small diameter.

Various loading conditions were applied when testing the structures. In each particular case, loading conditions were chosen depending on the type of the structure and the objective of the tests. The entire span should be loaded in order to get the maximum values of longitudinal forces in the panels of the upper and lower chords of structures of any shape, as well as the maximum values of structure deformations. The following loading conditions were considered:

- four point forces in all panel points of the upper chord;
- two point forces in the middle panel points of the upper chord;
- two point forces in the panel points of the upper chord outermost from the supports;
- two point forces in the panel points of the upper chord outermost from the left support.

In cases when more unfavorable conditions of structure elements' operation occur at partial loading, loading conditions with the load affecting the half of the span should be considered. That is why additional loading conditions were considered:

- uniformly distributed load along the entire span of the structure;
- uniformly distributed load along the half of the span of the structure.

An analysis of the loading conditions under consideration shows that, when the structure is loaded along the entire span, the maximum forces occur not only in the chords but also in the struts. Therefore, the loading conditions when four point forces affect all panel points of the upper chord were chosen to study the experimental structure. Such loading conditions match the actual operating load (uniformly distributed load along the entire span of the structure) the best. The requirements for beams used to manufacture the structure elements were adopted with account for such loading conditions.

Results and discussion

Stresses occurring in the elements of the tested structure at the design load q = 17.2 kN and assumed cross-sections of the elements are given in Table 1.

Table 1. Stresses in structure elements.

No.	Truss element	Notation	Force in elements, kN	Cross-section, mm	Stress, MPa		
					tension	bending	compression
1.	Beam elements of the lower chord	-	75.03	115 x 125	5.22	-	-
2.	Central beam elements	-	75.03	125 x 125	-	10.95	4.80
3.	Outermost beam elements	-	54.33	125 x 125	-	10.95	3.48
4.	Struts	1-2; 8-9	97.45	125 x 125	-	-	6.24
5.	Struts	2-3; 7-8	110.39	125 x 125	7.06	-	-
6.	Struts	3-4; 6-7	112.11	125 x 125	-	-	7.17
7.	Strut	4-5	51.74	125 x 125	-	-	3.31
8.	Strut	5-6	53.47	125 x 125	3.42	-	-
9.	Vertical posts	0_2-1; 0_8-9	19.14	125 x 125	-	-	1.22

For beams of C24 strength class, the characteristic values of strength in bending under a load applied to the edge is 24 MPa, compression along the grain — 21 MPa, and tension along the grain —14 MPa. In accordance with the EN 1995:2011 requirements, we determined the design strength values for beams of C24 class under these stress–strain states. The design values were: 14.8 MPa in bending with a load applied to the edge; 12.9 MPa in compression along the grain; and 8.6 MPa in tension. Besides, we calculated the design resistance for beams of C14 class in compression along the grain. The design value of stress for this stress–strain state is 9.8 MPa.

Tensions of 5.22, 7.06 and 3.42 MPa occur in the tension elements of the lower chord and in the tension struts. These stresses do not exceed the design values for C24 strength class. Therefore, structural beams of C24 strength class were used for these elements.

At the design load, bending stress R_b = 10.95 MPa occurs in the beam-columns of the upper chord of the structure, compression stress R_c = 4.80 MPa occurs in the central beam elements, and compression stress R_c = 3.48 MPa occurs in the outermost elements. Bending stress matching design resistance given for lumber of C24 strength class occurs in the upper chord elements. In addition to transverse bending, the elements undergo compression along the wood grain. Compression stress in the central elements is 4.8 MPa, and in the outermost ones — 3.48 MPa. These values do not exceed design resistance for C24 strength class, which makes it possible to use heartwood beams of C24 strength class for their manufacturing.

The compression struts and vertical posts undergo stresses of 6.24, 7.17, 3.13 and 1.22 MPa. The value of design resistance for lumber of C14 strength class, which is 9.8 MPa, exceeds these stresses. To manufacture this lumber, structural beams of C14 strength class were used (Rikynin and Vladimirova, 2012).

We calculated the percentage ratio of the volumes of wood consumed to manufacture beam elements with different stress–strain states. The corresponding values are given in Table 2.

Table 2. Ratio of the volumes of wood used to manufacture beam elements.

No.	Element and its stress–strain state	Volume of wood	
		m^3	%
1.	Tension beam elements of the lower chord, tension struts	1.286	48.7
2.	Beam-columns of the upper chord	0.921	34.9
3.	Compression struts and vertical posts	0.431	16.4
	TOTAL:	2.638	100.0

As follows from Table 2, almost 84% of the beams correspond to C24 strength class. Beams with a lower strength (C14 strength class) were used to manufacture the structure elements operating in compression along the grain. It is possible since the strength rates of beams in compression along the grain ensure resistance to the loads that occur in the elements when the structure is loaded. Thus, all the beams were used to manufacture the structure elements.

In the structure under consideration, the volume ratio of wood used to manufacture the structure elements with different strength matches the actual distribution of the strength values with regard to all the beams. However, an analysis of load-bearing structures' designs shows that, as for less tough wood, higher volumes are required to manufacture load-bearing structures (as compared to tougher wood). The actual strength distribution of the beams shows that tougher wood accounts for a higher volume than less tough wood. In other words, an inverse ratio is observed. In practice, it means that, when manufacturing load-bearing structures, some beams of higher strength are used while such strength is not required. Therefore, in order to use wood more efficiently and reduce material consumption in load-bearing structures, the sections of beam elements should be selected with account for the volume ratio of wood of different strength groups.

The structure was tested through load increase with an increment of 64 kN and deformation measurement. The panel points were made with the use of steel plates and cover plates with a thickness of 8 mm. They were attached to the chords and struts using self-tapping screws with a diameter of 6 mm and a length of 60 mm. The panel points attaching the struts to the chords were made using tube sections with an OD of 73 mm and a wall thickness of 8 mm. The forces from the axes (tubes) were transferred to the metal plates and cover plates, and then, to the wood through the self-tapping screws. The out-of-plane stability of the compression and tension chords was ensured with wood blocks interconnecting the chord beams in six places along the structure length in the compression chord and in four places — in the tension chord.

The deformations of the wood were determined using strain gauges with a base of 50 cm and dial gauges with a division value of 0.01 mm. Graphs showing structural deflections at incremental loading were constructed based on the measurements of the deformations obtained during the tests (Figure 3).

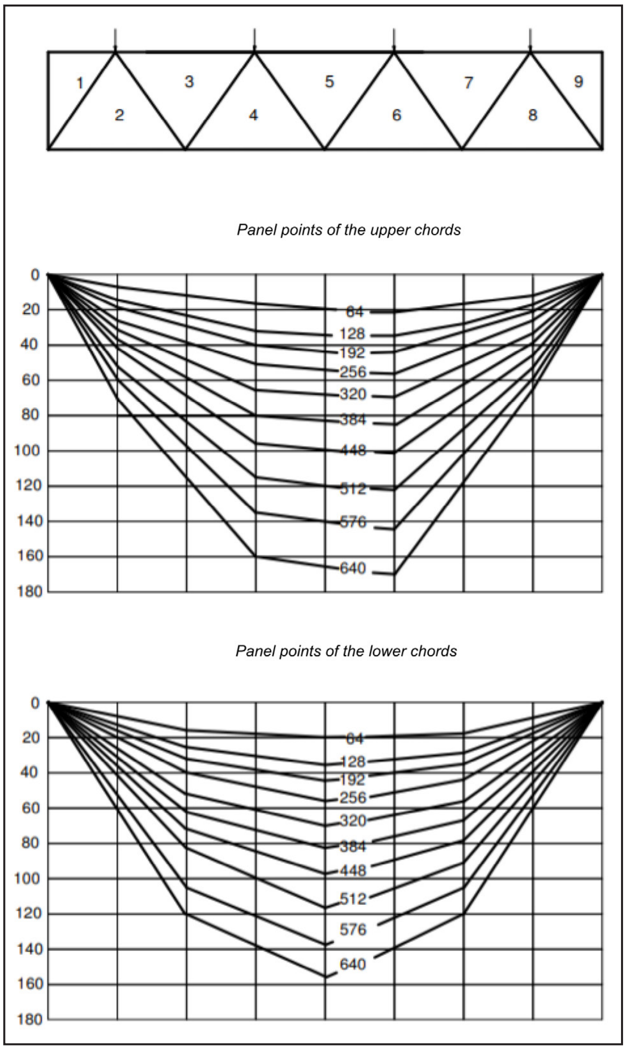

Figure 3. Graphs of structural deflections at incremental loading.

DOI: 10.23968/2500-0055-2020-5-2-25-31

The graphs make it possible to trace the displacement of the panel points of the upper chord. An analysis of the graphs shows that these displacements are asymmetrical with regard to the vertical axis. By comparing the stresses in the bars, calculated theoretically, with the data obtained during the tests, we observed a good fit. For example, in strut 2-3 (strain gauge M-5), the stress calculated theoretically is 14.85 MPa, while the experimental value is 12 MPa. In the compression chord – bar O_3-3 (strain gauge M-4), the stress calculated theoretically is 7.8 MPa, while the experimental value is 8.4 MPa. The destruction of the structure occurred at the tenth stage of loading, with a total load of 640 kN. The maximum deflection was 158 mm, or 1/112 of the span. The safety factor of the experimental structure was 2.0. The reason for the destruction was a crack in the ends of the compression strut beam. In addition, compression support struts broke in the panel points of the tension and compression chords. The head metal plate bent and the end of the beam element cracked in the panel point where compression strut 3-4 adjoined the chord. Further testing was stopped. Visual inspection showed that there were no apparent signs of the destruction of other structure elements. The tension joints were not destroyed. The chord elements and tension struts did not have noticeable deformations.

Conclusions

The following conclusions can be made as a result of the study:

1. There is a good fit between the calculated values of stress in the truss elements and the experimental data.
2. The structure was damaged in the panel points connecting the compression strut with the elements of the tension and compression chords. The tension elements and their joints remained undisturbed.
3. The experimental structure has a safety factor of 2.
4. The strength properties of heartwood beams make it possible to use them to manufacture load-bearing structures.

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DOI: 10.23968/2500-0055-2020-5-2-25-31

ПРОЧНОСТНЫЕ ХАРАКТЕРИСТИКИ ЭЛЕМЕНТОВ ФЕРМЫ ИЗ ЭКОЛОГИЧЕСКИХ КОНСТРУКЦИОННЫХ ПИЛОМАТЕРИАЛОВ

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Аннотация

Для изготовления несущих строительных конструкций широко применяются пиломатериалы хвойных пород. Качество круглых лесоматериалов используемых для изготовления таких пиломатериалов в последнее время постоянно снижается. Уменьшается диаметр лесоматериалов и в них часто встречается ядровая гниль. В статье рассматривается возможность изготовления элементов несущих конструкций из брусьев, получаемых из круглых лесоматериалов небольших диаметров, ранее не применявшихся для изготовления конструкционных материалов для строительства. Предлагается из таких лесоматериалов получать брусья с максимальным сохранением структуры ствола дерева – сердцевинные брусья. Эти брусья вследствие максимального сохранения кольцевой структуры годичных слоев древесины обладают более высокими прочностными характеристиками по сравнению с традиционно применяемыми конструкционными пиломатериалами. **Цель исследования.** Проверка прочностных характеристик элементов строительных конструкций, изготовленных из сердцевинных брусьев, выпиленных из круглых лесоматериалов небольшого диаметра. **Методы.** Испытание экспериментальной фермы из сердцевинных брусьев путем поэтапного загружения и доведения до разрушения. **Результаты.** Определены прочностные характеристики элементов фермы с элементами, изготовленными из сердцевинных брусьев, выпиленных из круглых лесоматериалов небольшого диаметра. Наблюдается хорошее совпадение рассчитанных значений напряжений в элементах фермы со значениями, полученными экспериментально. Разрушение конструкции произошло в узловых соединениях сжатого раскоса с элементами, растянутого и сжатого поясов. Растянутые элементы и их стыки остались неразрушенными. Экспериментальная конструкция имеет запас прочности равный двум. Двукратный запас прочности по сравнению с расчетной нагрузкой показал, что экспериментальная ферма обладает необходимой несущей способностью и является надежной конструкцией. Результаты исследований подтверждают, что прочностные характеристики сердцевинных брусьев соответствуют требованиям, предъявляемым к элементам несущих строительных конструкций. Прочностные характеристики сердцевинных брусьев позволяют применять их для изготовления несущих строительных конструкций.

Ключевые слова

Несущие строительные конструкции, прочностные характеристики брусьев, кольцевая структура годичных слоев древесины, испытания экспериментальной фермы.

CONSTRUCTION SYSTEM FOR THE ERECTION OF PREFABRICATED BUILDINGS OUT OF FACTORY-MADE MODULES

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Abstract

Introduction: The article presents a study and justification of the concept for the erection of prefabricated buildings out of modules on a pre-arranged foundation with a comprehensive assessment of quality, accuracy, constructability and safety of building superstructure blocks. **Purpose of the study:** Development of rapid construction is driven by the need for affordable housing in Russian towns and cities, the need for the erection of buildings of various purposes within short time frames in regions with severe and extreme climate. **Methods:** Prefabricated construction is a promising industry, but it is required to perform studies on the selection of optimal organizational and technological solutions, aligning those with modern standards and requirements. **Results:** The authors consider a method of choosing a technique for the construction of pile foundations for multi-purpose prefabricated buildings with account for the analysis of existing loads and structural features. Determination of constructability criteria makes it possible to assess the comparative efficiency of the prefabricated-construction techniques with account for data of geotechnical surveys, conditions of a construction site, etc.

Keywords

Construction systems, prefabricated buildings, module, pile foundations, constructability criteria.

Introduction

Further development and implementation of the advantages of the construction system for the erection of prefabricated buildings out of factory-made modules is complicated due to the lack of necessary justification for the use of modular systems in complex construction conditions, a single methodology of design, transportation, assembly and disassembly of prefabricated modular buildings, as well as the lack of production facilities for module manufacturing, or their poor technical condition (Anderson and Anderson, 2007; Wang et al., 2007).

The use of modernized building complexes will make it possible to create a construction system of prefabricated buildings made out of factory-made modules with a pre-arranged foundation, connected utilities, roads, public services and amenities, etc.

The duration of the construction of modernized building complexes should be determined at the preparatory stage for the production and manufacturing of modules at factories using robotic conveyor belts. In this case, the labor efforts can be distributed as follows: 80–90% — manufacturing at factories and 10–20% — manufacturing at the construction site.

When modules are delivered to the construction site by means of handling machinery and vehicles, their rational storage at manufacturers' warehouses will make it possible to reduce the transportation costs by 12–16% and idle hours of crews by 8% (on average).

To determine the optimal number of vehicles when designing schedules of their operation, several assembly processes and corresponding service vehicles can be combined into unified complex logistics systems.

The use of BIM when designing and developing a construction method statement and a work method statement makes it possible to promptly account for all design changes in real time. When a design is developed, it becomes possible to refer repeatedly to the database and compare alternative options of various technologies, select an optimal solution using the extensive database of regulatory data on materials, machinery, and working procedures. There is no need for graphic representation of a design, time-consuming calculations, extensive description, or standard schemes not related to the real conditions. The possibility of visual assembly of high-tech modular systems with a detailed elaboration of embedded utilities is the main advantage of this technology.

The foundation structure is usually chosen based on traditional approaches to the design process with account for the analysis of acting loads, design features of the structure, and geotechnical conditions of the construction site.

For buildings with less than four floors, it is expedient to erect foundations as solid monolithic slabs with a thickness of 350–400 mm, strip footings under support columns, columnar elements suitable for homogeneous soil conditions that rule out the differential settlement.

DOI: 10.23968/2500-0055-2020-5-2-32-37

For high-rise buildings or construction in soft water-saturated heterogeneous soils, pile foundations shall be considered with slab or strip rafts (more rarely — with stand-alone rafts).

When high-rise buildings are constructed, a combined piled-raft solution is the most reliable. In this case, during building operation, a part of the load from the piles will be transferred and redistributed to the raft slab (up to 20%).

Materials and methods

Construction system for the erection of prefabricated buildings out of factory-made modules. It is impossible to improve construction systems for the erection of prefabricated buildings out of factory-made modules without a methodology and a set of R&D and experimental developments using state-of-the-art technical equipment, control and measurement instrumentation, as well as software & hardware diagnostics and online monitoring systems (Nadim and Goulding, 2010; Knaack et al., 2012).

The issue becomes even more relevant when quality, reliability and safety requirements are raised for the assembly, disassembly, transportation, and operation of prefabricated buildings of various purposes, especially in unfavorable construction conditions (Afanasyev, 1998, 2000; Kazakov, 2004; Verstov and Badjin, 2010).

Modernization of prefabricated construction means improvement and optimization of all processes, development and introduction of new equipment, materials, production methods, the need for retrofitting and upgrading production facilities through new computer technologies while reducing energy consumption (Sychev, 2015a, 2015b).

When solving tasks for the optimization of process solutions for the erection of prefabricated buildings out of factory-made modules, a game-theory model in the form of a process graph has been used that includes individual blocks and elements of the operation cycle and schemes providing an efficient prefabricated-construction technology.

Choosing foundation construction methods. Two methods are used in practical foundation engineering: installation of factory-made solid, reinforced-concrete and prismatic piles using various techniques, and installation of bored cast-in-situ piles.

Factory-made piles can be installed in three ways: by driving, by jacking, or by vibration. Besides, the following cast-in-situ techniques are widely used:

A. Bored piles with soil removal:

- a pile is installed by rotation drilling with a borehole being washed with slurry;
- a pile hole is made using a continuous flight auger;
- piles are installed using casing with soil removal by augers or special drilling tools fixed to an extension rod;
- piles are installed using reinforced-concrete shells inserted by vibration with soil removal from the internal space of the shells by a vibration clamshell bucket fixed to the rope of a hoisting machine;
- double rotation using a rotating casing pipe, inside which a flight auger operates.

B. Cast-in-situ piles without soil removal:

- a hollow casing pipe with a sacrificial shoe is screwed in. As the pipe is removed, the cavity in the soil is filled in with concrete;
- sinking of a casing pipe with a sacrificial shoe by vibration;
- driving of a casing pipe with a sacrificial shoe and its removal using a vibration generator;
- a casing pipe equipped with a displacement auger is screwed in. As the pipe is removed, the cavity is filled in with a concrete mix displacing the soil from the pile hole (the method is also called “displacement piling”) (Judina et al., 2013; Verstov and Judina, 2015).

Each of the listed techniques has its advantages and disadvantages in specific geotechnical conditions. For example, the use of factory-made piles means the guaranteed quality of the pile shaft, high performance, and relatively low cost for the installation of a linear meter of a pile. The disadvantage of this technique is limitations on the dimensions and bearing capacity, and dynamic effects on the environment during pile sinking.

The advantage of cast-in-situ techniques is in the universal dimensions (length — up to 80 m, diameter — 0.2–2.0 m) and possible transmission of large loads on the soil (more than 3000 tons), and the main disadvantage is that they do not guarantee pile shaft integrity, especially when works are performed in soft soils.

Therefore, it is especially important to choose expedient techniques of pile foundation construction as early as at the stage of site preparation for development and when the developer sets a design assignment with account for the requirements for the techniques depending on the location of the facility:

- when the area for development is free, construction works can be conducted without limitations on the dynamic effects in the soil;
- when works are performed in a build-up area, we should consider the distance from the existing buildings and structures to the facility under construction, i.e. so-called areas of responsibility: whether they are adjacent, at a distance of less than 20 m, 20–30 m or more than 30 m.

The foundation construction method is chosen based on an analysis of the integrated quantitative specification of different methods of preparatory works, which makes it possible to assess the efficiency of their use in a single rating scale with account for different geotechnical conditions of construction sites (Gaido, 2011; Gaido et al., 2012).

Results

Construction system for the erection of prefabricated buildings out of factory-made modules

The erection of prefabricated buildings out of factory-made modules on a pre-arranged foundation with ready-made infrastructure (roads, public services and amenities, utilities, etc.) makes it possible to construct buildings within short time frames in complex and extreme climatic and geological conditions.

Utility lines are embedded in the structural modules of load-bearing walls and floor slabs, and finishing is made at the factory. The frame structures are connected by means of high-strength bolts.

A general view of a construction system for the erection of prefabricated buildings out of factory-made modules and its main structural elements are given in Figure 1.

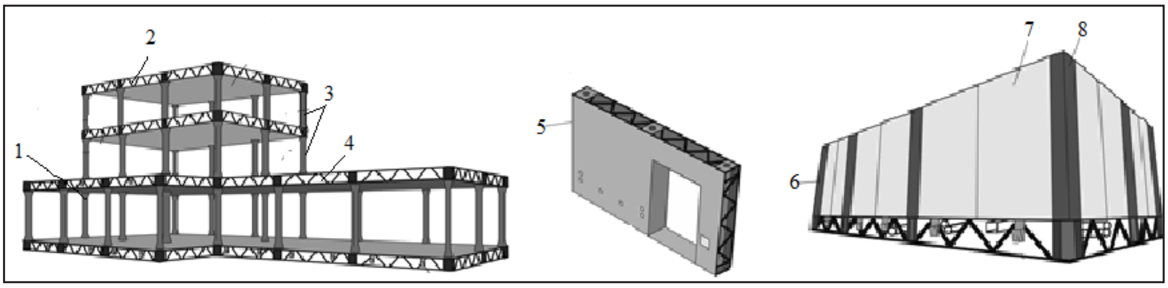

Figure 1. A construction system for the erection of prefabricated buildings out of factory-made modules
1 — a construction system including standard modules assembled; 2 — a floor slab; 3 — support columns; 4 — embedded utility lines; 5 — load-bearing walls; 6 — a general view of the construction system; 7 — enclosure panels; 8 — insulated glazing.

The tools and techniques ensuring accuracy, quality and automation of assembly methods for prefabricated buildings allow for the assembly of modules and their transportation to the construction site as well as prompt quality control. The table below presents the technical and economic indicators of assembly methods for prefabricated buildings made out of factory-made modules.

Table 1.

Indicators	Module assembly methods				
	Non-restricted	With partial confinement of movement	Semi-restricted	Sem-automated	Automated assembly using robots
element fixation	w/o stoppers	with stoppers	guide or movable truss	box-unit group guide	assembly bench
equipment	flexible ropes	cross beams with flexible connections	cross beams with rigid connections	guide with rigid clamps	robotic arm
accuracy of assembly	up to 20 mm	up to 7.5 mm	up to 5 mm	up to 2 mm	up to 0.1 mm
labor intensity, %	100	75	60	45	30
cost, %	100	85	70	50	40
duration, %	100	60	50	20	10

Choosing foundation construction methods

The foundation construction method is selected based on an analysis of the values of constructability criteria: integrated specification of different methods of preparatory works (foundation construction), which makes it possible to assess their comparative efficiency in a single rating scale with account for different geotechnical conditions.

Constructability is evaluated by three levels of criteria: integral criteria; generalized criteria for the evaluation of pile foundation construction options (production, reliability, and quality), differential or simple criteria (technical and economic indicators).

Production criteria characterize a technique under consideration in terms of labor intensity, minimum required area dimensions, and transportation capacity of a drilling rig or a pile driver. Constructability, which determines quality and reliability, characterizes techniques in terms of negative impact on the environment (air emissions, noise emissions, soil contamination with drilled cuttings, etc.) and existing buildings and structures in the form of their deformations.

Simple criteria (technical and economic indicators) characterize techniques in terms of cost of works, material costs, and additional technological actions.

To evaluate constructability for each option, all criteria should be measured in commensurable values: integral — $0 \le J_i \le 1$; generalized — $0 \le m_i \le 1$; differential — $0 \le m_{ij} \le 1$.

To meet the above condition, all particular values xij are transformed into dimensionless quantities using the following equations:

$$m_i = \frac{x_{ij}}{x_1^{\max}}, \quad (1)$$

DOI: 10.23968/2500-0055-2020-5-2-32-37

$$m_{ij} = \frac{x_i^{\min}}{x_{ij}}, \qquad (2)$$

Equation (1) is used when an increase in the indicator under consideration results in an increase of the generalized and integral criteria, otherwise, equation (2) should be applied.

The generalized and integral criteria are calculated using the following equations:

$$m_i = \sum_{i=1}^{n} m_{ij} K_i^{generalized}, \qquad (3)$$

$$J_i = \sum_{i=1}^{n} m_i K_i^{\text{int}egral}$$

where $K_i^{generalized}$, $K_i^{integral}$ are the weight coefficients of the i^{th} generalized and integral criteria, respectively, determined using the Delphi method (polling of experts in foundation engineering).

This method allows us to choose techniques for the construction of pile foundations for prefabricated buildings under various conditions of construction sites.

Let us consider the use of the above method in various situations.

Construction of a prefabricated building in soft water-saturated clayey soils on an undeveloped construction site

For such conditions, a foundation on prefabricated reinforced-concrete piles (quantity — 297, length — 22 m, cross-section — 350 x 350 mm) or cast-in-situ piles (diameter — 450 mm) will be required. The design load per pile is 1200 kN.

Leaving out intermediate calculations, we obtain a ranked list of various techniques for the construction of pile foundations in descending order, which includes technique names and corresponding values of constructability criteria (J_i):

1. Percussion drilling of factory-made reinforced-concrete piles ($J_i = 0.75$).
2. Installation of cast-in-situ piles by driving of a casing pipe and its vibratory removal ($J_i = 0.71$).
3. Installation of cast-in-situ piles with screwing-in of a casing pipe with a sacrificial shoe ($J_i = 0.69$).
4. Installation of cast-in-situ piles using the displacement method ($J_i = 0.68$).
5. Installation of drilled piles using flight augers ($J_i = 0.60$).
6. Installation of drilled piles using slurry ($J_i = 0.55$).

The ranking analysis shows the following:

- percussion drilling of factory-made reinforced-concrete piles — constructability criterion $J_i = 0.75$ (the largest value) — is the most efficient.
- installation of piles with constructability criteria J_i = 0.60 and 0.55 is not recommended. Such works in soft soils lead to the loss of pile shaft quality (such defects as fractures and necking, voids, frame denudation, etc.). It should be noted that, in Europe, driving of prismatic piles is rarely used for civil engineering purposes.

Construction of foundations for prefabricated buildings near existing residential houses (space-limited environment)

For the implementation of the project, we will consider pile foundation (325 piles, length — 28 m, cross-section of a factory-made pile — 400 x 400 mm) or a cast-in-situ pile foundation (diameter of a pile — 520 mm). The design load per pile is 1400 kN.

As a result of constructability criteria determination for the space-limited environment, we obtain the following ranked list of techniques for the construction of pile foundations in descending order:

1. Jacking of factory-made reinforced-concrete piles ($J_i = 0.80$).
2. Installation of cast-in-situ piles with a screwing-in of a casing pipe with a sacrificial shoe ($J_i = 0.79$).
3. Installation of drilled piles using the displacement method ($J_i = 0.78$).
4. Installation of drilled piles using flight augers ($J_i = 0.70$).
5. Installation of drilled piles using slurry ($J_i = 0.61$).
6. Installation of drilled piles in casing pipes using a kelly bar ($J_i = 0.60$).

The results obtained show that the method of jacking factory-made piles has the best constructability criterion value: $J_i = 0.80$. However, it should be noted that this technique is efficient for design loads per pile up to 1500 (1600) kN. For loads exceeding these values, cast-in-situ pile construction should be used.

Besides, during pile jacking or when the displacement method is used near existing buildings with performance exceeding 200 linear meters of piles per shift, the soil and the existing structures may rise, which will lead to extra differential settlements. To avoid such negative consequences, calculations should provide for “protection” measures such as sheet piling, restricted performance, preliminary soil loosening with flight augers, reducing soil resistance.

Conclusion

Improvement and modernization of construction systems for prefabricated construction out of factory-made modules (as compared to new construction) increase performance per worker by 35–40%, save capital investments in general construction works by 25–30% since they do not include costs for preparatory works (excavation works, foundation construction, laying utility networks, etc.).

The method of choosing the foundation structure and techniques of its construction in case of multi-purpose prefabricated buildings, based on an analysis of advantages and disadvantages of pile foundation construction techniques and determination of constructability criteria, makes it possible to determine the efficiency of their use in prefabricated construction with account for data of geotechnical surveys, conditions on a construction site, etc.

The practical relevance of the study lies in the establishment of the scientific framework for the integrated modernization of the prefabricated-construction system.

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DOI: 10.23968/2500-0055-2020-5-2-32-37

СТРОИТЕЛЬНАЯ СИСТЕМА ВОЗВЕДЕНИЯ ПОЛНОСБОРНЫХ ЗДАНИЙ ИЗ ГОТОВЫХ МОДУЛЕЙ

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Аннотация

Введение. В статье представлено исследование и обоснование концепции возведения полносборных зданий из модулей на готовом фундаменте с комплексной оценкой качества, точности, технологичности и безопасности возведения надземных частей зданий. **Цель исследования.** Развитие скоростного строительства обусловлено потребностью в доступном жилье в малых и средних городах России, необходимостью возведения зданий различного назначения в короткие сроки в районах с суровыми и экстремальными условиями. **Методы.** Полносборное строительство является перспективным, но необходимы исследования по выбору оптимальных организационных и технологических решений, приведение их в соответствие с современными требованиями и нормами. **Результаты.** Рассмотрена методика выбора способов устройства свайных фундаментов многофункциональных сборных зданий с учетом анализа существующих нагрузок и конструктивных особенностей здания. Расчет критериев технологичности позволяет определить сравнительную эффективность их применения для полносборного строительства с учетом данных инженерно-геологических изысканий, условий строительной площадки и т. п.

Ключевые слова

Строительные системы, полносборные здания, модуль, свайные фундаменты, критерии технологичности.

Geotechnical Engineering and Engineering Geology

SPECIFIC FEATURES OF THE CONSTRUCTION AND QUALITY CONTROL OF PILE FOUNDATIONS IN ENGINEERING AND GEOLOGICAL CONDITIONS OF SAINT PETERSBURG

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Abstract

Introduction: The article reviews various methods of the construction and quality control of pile foundations in complex geological conditions of Saint Petersburg. The authors describe conditions, under which the geological structure of the city was formed. They list the main factors affecting the selection of foundation types and methods of their construction, describe soil properties influencing the quality of piles. **Methods:** Methods of pile construction based on different drilling technologies are presented (bored piles, pre-fabricated piles, displacement piles (with soil compaction and extraction)). Various methods of the quality control of piles constructed are also described (seismoacoustic, ultrasonic). **Conclusions:** Based on the results of the study, it is concluded that pile quality control methods shall be widely used and their applicability shall be extended. **Discussion:** It is suggested to improve methods of pile foundation integrity testing, increase their use on construction sites, study their applicability not only to detect defects in a pile but to control the quality of construction and materials used.

Keywords

Geology, foundations, pile technologies, control methods.

Introduction

Due to the specifics of their formation, the engineering and geological conditions of Saint Petersburg are rather complicated in geotechnical terms. They are characterized by a high stratification diversity, sandy and silty-clayed varieties alternating in depth, which contributes to their anisotropy in terms of water impermeability as well as physical and mechanical properties. A distinctive feature of the engineering and geological section in the historical districts of the city is the availability of thick soft soils represented by water-saturated silty-clayed varieties with organic inclusions. Due to their thixotropic properties, such soils can change their physical-and-mechanical, strength and deformation characteristics under the various dynamic or mechanical impact. Since morainic deposits are located at a depth of 16–18 m and lower, installation of pile foundations for new construction and foundation strengthening in historical buildings is a reliable and rational solution in terms of engineering.

One of the important criteria that determine the reliability of a pile foundation is the quality of works performed, conformance of the actual execution to the design. Among important qualitative parameters of pile construction, the following can be distinguished: the load-bearing capacity of a pile, pile penetration to the design depth (soil bearing layer), and integrity (continuity) of a pile body throughout its length. Such defects as caverns, voids, cracks, and significant splits in a pile body, or a pile toe failure to reach the design depth lead to the occurrence of non-uniform deformations, a decrease in the load-bearing capacity of the pile foundation, formation of cracks, or tilting, which is unacceptable. In construction, pile integrity and penetration depth are determined by seismoacoustic and ultrasonic methods. This review paper addresses and systematizes methods of non-destructive testing of different pile foundations constructed in soft water-saturated silty-clayed soils.

1. Engineering and geological conditions of Saint Petersburg

DOI: 10.23968/2500-0055-2020-5-2-38-45

In geological terms, soft soils are alluvial soils of different composition and origin that were not sufficiently consolidated under natural conditions. Such soils can be divided into three groups by their formation and occurrence: 1) lacustrine and marine deposits producing bedded formations (sands, sand clays, loams, clays, organic and mineral silts); 2) covering deposits (peats, clayey residual deposits of bed rocks, loess); 3) technogenic deposits. Soft soils are located almost all over the north-west areas, in particular, in Saint Petersburg, where landscape formation, stratification of soils, and their physical-and-mechanical properties are determined by the history of the geological evolution of the area in the Quaternary period (Dashko et al., 2011).

According to L. G. Zavarzin, the area of the city can be divided into three main soil complexes. The first one is mostly spread in the north of the city. It represents sands and light sand clays with relatively good structural properties, occurring from the surface to a considerable depth. The second one is mainly characteristic of the southern part of the city. It is distinguished by its favorable soil conditions represented by the Luga moraine occurring in the upper part of the natural bed. The third soil complex is associated with the formation of the Neva River and its delta, which resulted in the deposits of fine-grained and silty sands with a layer thickness of 2–5 m, underlain by a thick layer of soft lacustrine-and-glacial and marine deposits. Their thickness is usually within a range of 20–30 m. These deposits are represented by silty sands, sand clays, loams, and clays, layers of which may contain lenses and bands of peaty soils. Such soils are characterized by high natural moisture, porosity, high and non-uniform compressibility, heaving, and thixotropy (Mangushev and Osokin, 2010).

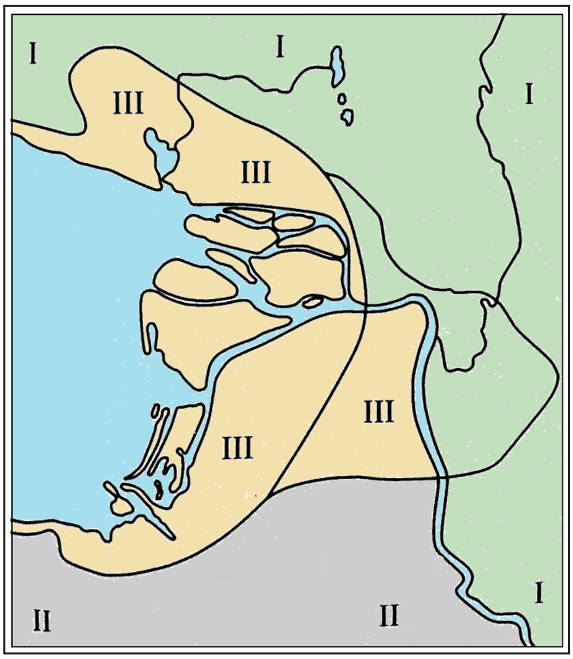


Figure 1. A map of the city area divided into soil complexes.

Then, there is a gradual transition from the mass of lacustrine-and-glacial deposits to the moraine top, occurring at depths of more than 10 m. It is this soil mass that is most often used for the implementation of construction projects in Saint Petersburg in terms of the construction of pile foundations for buildings and structures.

The primary deposits that occur in the lower part of the natural bed are characterized by a high degree of consolidation. In the southern part of the city, the structure of the upper stratum includes Lower Cambrian clays. Upper Kotlin clays are found under the Quaternary period stratum in the northern and central parts of Saint Petersburg, as well as under the Lower Cambrian clays in the southern part. These soil deposits are considered firm and serve as a confining layer.

2. Practical application of pile-construction technologies in Saint Petersburg

Modern construction uses various types of piles: pre-fabricated piles (driven piles inserted by pressing or vibration); cast-in-situ piles (bored, displacement, and drilled injection piles).

Currently, driven piles (Figure 2) are mainly used for residential and industrial construction in the peripheral areas of the city. As for residential and industrial construction, 25% of all pile works are performed with the use of driven piles.

a)

b)

Figure 2. Pile driving equipment (a) and types of defects in driven piles (b).

The main defects of driven piles in terms of integrity include cracks, splits, distortion of joints in sectional piles, and pile head destruction during installation.

In the built-up areas of the city, pile construction by jacking (by means of both Russian and imported equipment) is widely used (Figure 3). Piles are hydraulically gripped and jacked into the ground. By testing the integrity of such piles, we can determine defects occurring during installation (splits, cracks) and control the penetration depth when it is not possible to reach the design level due to stiff intermediate layers or solid inclusions.

Figure 3. Pile construction by jacking.

Today, displacement piles account for a significant share in the market of pile works (up to 45%). Such piles include piles made by the Fundex or DDS (Drilling Displacement System) technology. These two types of technologies differ in the method of pile construction. When the Fundex technology is used, a pile hole is made by rotating and pressing the “sacrificial drill bit – drill pipe” system to a given depth, then a cage is lowered through the open top of the pipe, and concreting is performed. Due to its particular advantages, this pile construction technology is in demand in Saint Petersburg. However, significant constructions risks and possible defects typical for the technology shall be noted: for instance, some authors (Mangushev et al., 2014) state that, during pile design studies, concrete-mixture stratification is observed, and in some soil conditions, the pile diameter reduces with the formation of necking (Figure 4b).

a)

b)

Figure 4. Pile construction using the Fundex technology (a) and a necking defect along the length of the pile shaft (b).

The DDS technology involves the excavation of a pile hole with a working tool without soil removal due to compaction. A drilling tool with a compaction system is lowered to the design level, then it is pulled back with the simultaneous pile-hole concreting, and after that, the pile hole is reinforced with a reinforcement cage. Among the disadvantages of the technology, changes in the pile shaft (formation of bulging) during concrete feeding under pressurization shall be noted, which leads to the excess consumption of concrete (Figure 5).

a)

b)

Figure 5. Pile construction using the DDS technology (a) and pile shaft bulging with the excess consumption of concrete (b).

The CFA (Continuous Flight Auger) method is another leading method among modern pile construction technologies (Figure 6). This technology is widely used in soils of different density and it is especially effective when penetrating thick strata of sand, semi-hard and stiff loams where it is not possible to use displacement piles. Pile hole concreting is performed using a concrete pump (concrete is fed through an inner tube of the working tool) with the auger being simultaneously removed. Immediately after the auger has been completely pulled out, a reinforcement cage is lowered into the concrete mixture. The CFA technology is distinguished by the following crucial aspect: auger flights have an active influence on the soil mass, which limits the use of the technology in soft soils where the deformation modulus is less than 5 MPa and the internal friction angle is less than 10°. Piles constructed by the CFA technology shall be tested for integrity.

Figure 6. Pile construction using the CFA technology.

DOI: 10.23968/2500-0055-2020-5-2-38-45

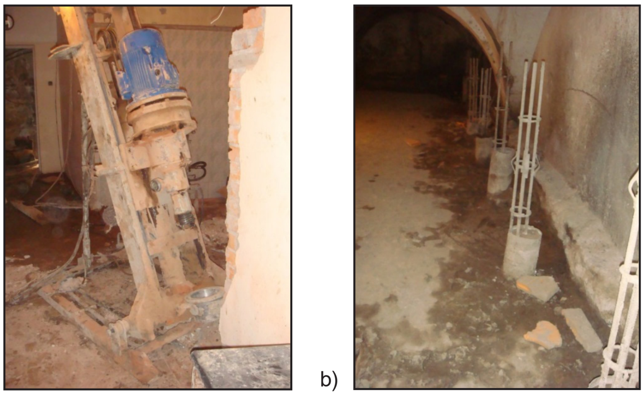
In geotechnical engineering and foundation engineering, the technology of pile drilling using a casing tube is considered a universal and traditional method, although it has a very small market share of 4%. This technology is used in the construction of foundations with a high load-bearing capacity, for bridge substructures, as well as for piles at significant depths over 40 m. The process of pile construction based on this technology consists in lowering a section casing pipe to the design level by progressive rotation. Then, the soil is extracted from the casing pipe using drilling tools (section by section), a reinforcement cage is installed, and concreting is carried out using the tremie pipe (vertically moving pipe) method. The technology has the following advantages: a reduced impact on foundation soils, which makes it possible to perform operations near the surrounding buildings; a wide range of piles in terms of size and depth. However, caverns and voids can generate in soft soils. Therefore, integrity testing is required.

a)

b)

Figure 7. Pile construction with a casing pipe(a); a cavern in a drilled pile (b).

In Saint Petersburg, drilled injection piles are used to strengthen bases and foundations in the existing buildings and structures under reconstruction or restoration. Drilled injection piles can be constructed in the existing foundation, which makes it possible to transfer the load from the building to deeper layers of the soil body. To construct such piles, a pile hole is drilled by core drilling through the foundation and then through the soil body using slurry (by rotary drilling rigs) (Figure 8). After that, the pile hole is filled up with a cement mortar through a drill string. Immediately after cementing, a reinforcement cage is installed, which is lowered section by section. The sections are joined by welding.



a) b)

Figure 8. Construction of drilled injection piles using a small drilling rig (a); heads of drilled injection piles used for underpinning (b).

It shall be noted that in soft soils, a small-diameter pile experiences significant bending moments and, therefore, strains. To control the reliability and quality of piles constructed, integrity testing shall be conducted. It is used to identify possible cracks and determine the actual diameter of bored piles.

3. Methods of pile integrity testing in soft soils

In the regulatory documents used in the 1990s, e.g. Construction Rules and Regulations SNiP 3.02.01-87 “Earthworks, grounds and footings” (Ministry of Construction, Housing and Utilities of the Russian Federation, 2017), the following parametric characteristics of in-process control were used to assess the quality of drilled piles: elevations of the top, bottom and enlargements; pile hole diameter; perpendicularity of the pile hole axis. For the piles constructed by the method of underwater concreting, pile integrity was determined as the absence of discontinuities in the pile shaft. Samples taken from drilled out cores or by other means were tested to check pile integrity. It was pointed out (Construction Rules and Regulations SNiP 3.02.01-87 “Earthworks, grounds and footings” Clause 11.28) (Ministry of Construction, Housing and Utilities of the Russian Federation, 2017) that, in order to determine shaft integrity in drilled piles constructed by the method of underwater concreting, samples taken from drilled-out cores should be tested randomly, or integrity should be checked using non-destructive methods. It also was noted that such tests should be applied once for every hundred piles but no less frequently than for two piles at the facility, as well as for all piles constructed with violations of the technology.

The applicable building regulations state that, during pile-foundation construction, it is required to perform total or random quality control depending on the objectives as well as the nature and degree of defects and damage. Total quality control includes the determination of integrity along the length by the seismoacoustic method and the evaluation of concrete homogeneity by the radioisotope or ultrasonic methods (Construction Rules and Regulations SNiP 3.02.01-87 “Earthworks, grounds and footings”, Clause 12.8.1) (Ministry of Construction, Housing and Utilities of the Russian Federation, 2017). Random quality control of pile concrete includes the following operations:

- drilling-out cores to the full length in the amount of 2% of the total number of piles made of cast-in-situ concrete on the site but no less than two piles; testing concrete samples made of the cores for uniaxial compression;

- controlling pile length and assessing pile integrity using seismoacoustic tests: 20% of the total number of piles on the site;

- assessing pile concrete quality (homogeneity) to the full length by means of radioisotope and ultrasonic measurements: 10% of the total number of piles on the site.

Let us demonstrate some defects that may occur in piles on a construction site (Figure 9):

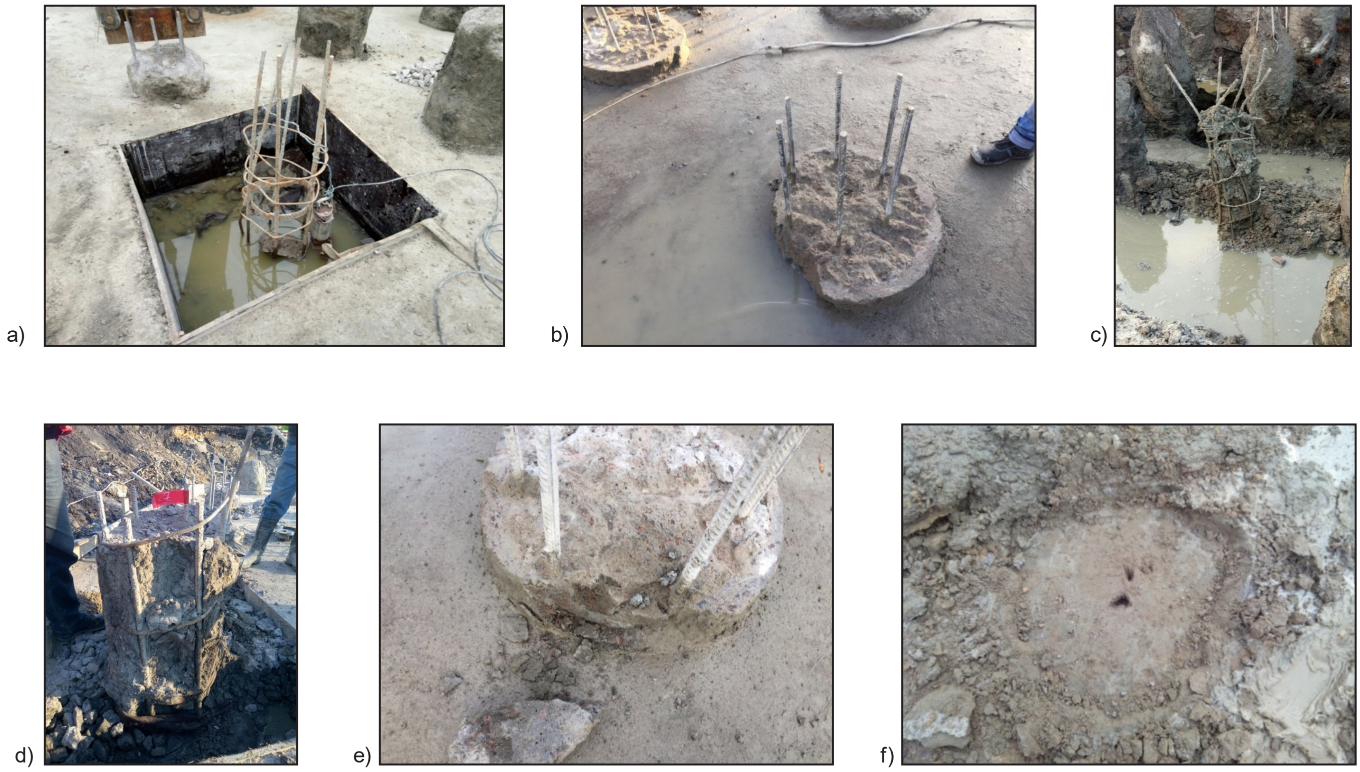


Figure 9. Defects occurring in cast-in-situ piles: a) absence of concrete in a pile head; b) deviation of the reinforcement cage from the design position; c) availability of a sludge layer in a pile head; d) violation of pile integrity; e) absence of a protective layer of reinforcement; f) formation of voids and caverns under the influence of underground waters with local of constant head (so-called “weeping pile”).

Let us list some technological defects that have a significant effect on the load-bearing capacity of piles: cold joints, caverns, voids during concreting; necking or bulging in the pile body; shrinkage or force-induced cracks; effect of “weeping piles”; non-uniform pile shaft formation in terms of density and material due to violations of concreting technology, etc.

In case of bored piles, the defects mentioned cannot be detected visually since they are hidden and localized along the length of the pile shaft. To solve the task, non-destructive testing and drilling-out of cores from the pile shaft are performed.

Drilling-out of cores remains a direct method of integrity testing for cast-in-situ piles (Figure 10). Since it is a traditional method, let us turn our attention to its modern peculiarities. To collect core samples, core barrels with diamond or carbide drill bits are used. The cores are then marked and a sampling report is made that includes the pile number and the number of samples with their diameter and depth indicated. The cores are tested for compression in the same way as concrete samples.

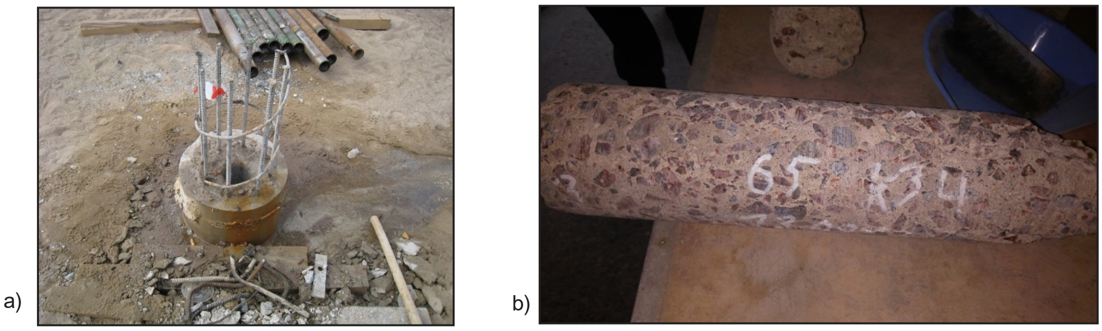


Figure 10. A pile hole used for core sampling (a) and a drilled-out core (b).

DOI: 10.23968/2500-0055-2020-5-2-38-45

One of the modern methods of pile integrity analysis, which makes it possible to determine the defect nature and its location along the pile length, is the seismoacoustic method. The principle of seismoacoustic instruments' operation is based on recording the parameters of elastic waves generated in piles by means of impact pulse. A wave is generated that propagates through the pile body at a certain velocity *V*, partly reflecting from the interface between the two media (e.g. concrete and soil) and the defects. The reflection of the wave is caused by a change in the acoustic impedance determined by the following equation:

$$Z=A\sqrt{(\rho\cdot E)}\ ,$$

where *A* is the area of pile cross-section; ρ is material density; *E* is the modulus of elasticity.

The reflected wave returns to the top of the pile and is recorded by an accelerometer (acceleration sensor), which, in turn, converts the waves generated by the wave exciter into a reflectogram (sound wave velocity vs. pile length or time graph) (Figure 11).

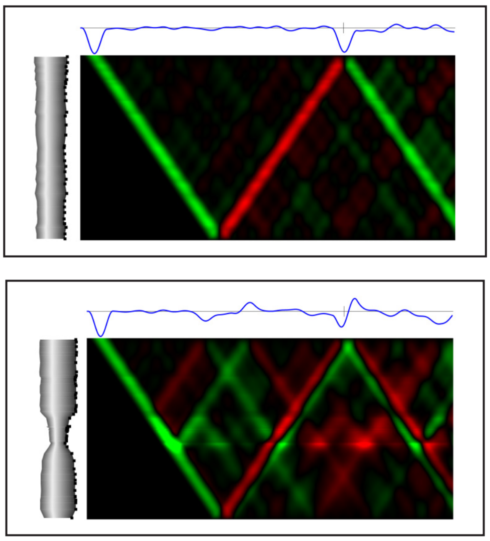

a)
b)

Figure 11. Reflectograms for a pile without defects (a) and for a pile with a necking defect (b).

In geotechnical practice, the ultrasonic flaw detection method is used for the integrity testing of drilled piles. It is based on the principles of ultrasonic wave velocity variation, the shape and amplitude of received signals depending on the physical and mechanical characteristics as well as the structure of the medium.

When applying this method, special tubes welded to the reinforcement cage are installed in a pile, which then used to conduct investigations. Concrete integrity in a pile can be assessed based on the energy transmission time and the energy value. If these parameters are constant or slightly vary with the penetration depth, it can be concluded that the structure is homogeneous. An increase in the signal transmission time and a decrease in the wave energy indicate the presence of defects, which is also shown on the instrument display.

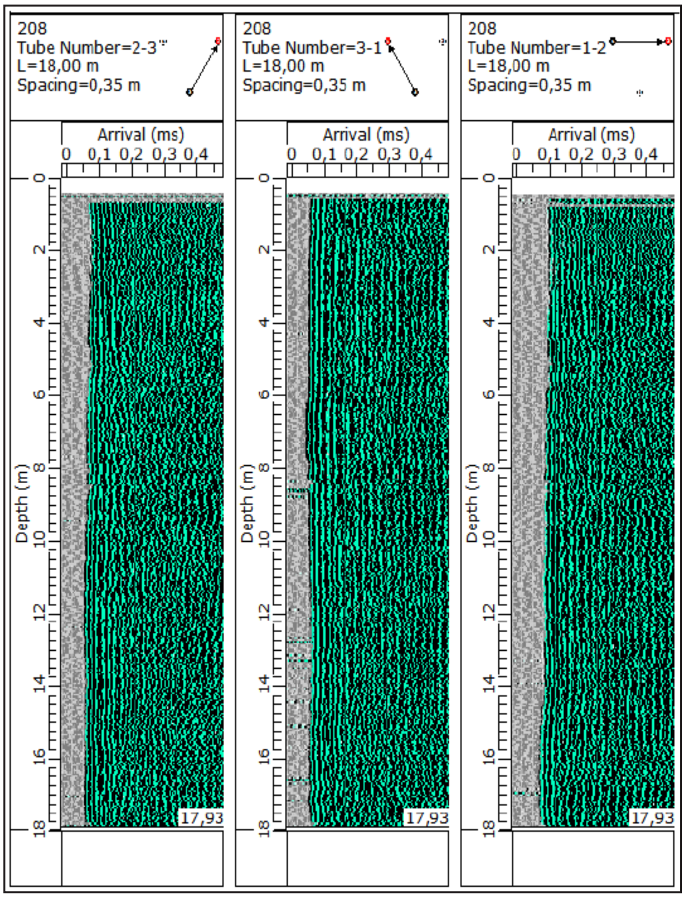


Figure 12. Ultrasonic scanning of a pile.

Conclusions

As experience in the integrity testing of cast-in-situ piles shows, the use of the ultrasonic and seismoacoustic non-destructive methods to determine pile integrity and pile installation depth is regulated by the corresponding documents and required in modern construction to detect defects and destruction of pile foundations to be installed. It should be noted that no regulations have been developed yet that would define the specific features of pile integrity testing for various technologies of pile construction in soft water-saturated soils, which makes the research conducted by the authors relevant and in demand in practice.

Due to the increasing application of bored piles, a need arises to control the depth of pile penetration into the bearing soil layer (reaching the design penetration depth).

In our opinion, the ultrasonic and seismoacoustic methods of testing are the most cost-efficient, less labor-consuming, and effective on construction sites. Interestingly, the methods used today for pile foundations' testing have their own characteristic features, require studying their applicability, establishing a relationship with the conditions of pile construction, and performing a correct interpretation of the results obtained in different soil conditions.

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DOI: 10.23968/2500-0055-2020-5-2-38-45

ОСОБЕННОСТИ УСТРОЙСТВА И КОНТРОЛЯ КАЧЕСТВА СВАЙНЫХ ОСНОВАНИЙ В ИНЖЕНЕРНО-ГЕОЛОГИЧЕСКИХ УСЛОВИЯХ САНКТ-ПЕТЕРБУРГА

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Аннотация

В данной статье обзорно рассматриваются различные методы устройства свайных фундаментов на территории Санкт-Петербурга в условиях сложного геологического строение, приведены различные методы контроля качества выполняемых свайных оснований. Обозначены условия, в которых формировалось геологическое строение территории города Санкт-Петербурга. Приведены основные факторы, влияющие на выбор видов фундаментов и методы его устройства, описаны свойства грунтов, которые оказывают влияние на качество выполняемых свай. **Методы.** Рассмотрены различные методы устройства свай по технологиям бурения: сваи, выполняемые в грунте, сваи заводского изготовления, сваи с уплотнением грунта и его извлечением. Описаны также различные методы контроля качества выполненных свай: сейсмоакустический, ультразвуковой. **Выводы.** По результатам работы сделан вывод о критической необходимости повсеместного использования методов для контроля качества свай и расширения спектра применяемости данных методов. **Обсуждение.** К обсуждению предлагается усовершенствование методов контроля сплошности свайных оснований, увеличение их практического применения на строительных площадках, изучение возможности их применения для контроля не только наличия дефектов в самой свае, но корректности их исполнения и качества применяемых материалов.

Ключевые слова

Геология, фундаменты, свайные технологии, методы контроля.

Surface Transportation Engineering Technology

QUANTUM QUARRYING LIFT-AND-TRANSPORT MACHINERY (QQLTM)

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Abstract

Introduction: Mastering of the methods of energy extraction from the physical vacuum and their implementation in engineering will change the motion mechanics and the pattern of using lift-and-transport machinery if those are equipped with quantum engines (QEs). **Purpose of the study:** The study is aimed to develop a conceptual foundation and a working hypothesis for the operation of quantum quarrying lift-and-transport machinery (QQLTM). **Problem statement:** The paper addresses challenges of rock transportation from the pit bottom to the upper levels. **Methods:** The thrust vector is decomposed into orthogonal components. A QQLTM force balance and motion equation is derived. Typical modes of QQLTM operation are determined. Calculations as well as graphical-and-analytical studies are performed. **Results:** The paper presents the results of calculations regarding time and energy consumption required for rock transportation, describing the motion of loaded QQLTM during rock transportation from the pit bottom to the transfer station and the upper level of a quarry. **Discussion:** The existing groups of motor and railway vehicles as well as lift-and-transport machinery can be substituted by groups of transport machines with QEs — QQLTM. This will allow for the significant improvement of quarrying technology, implementation of continuous cargo transportation without transshipment, reduction of energy consumption as well as material expenditures and labor efforts.

Keywords

Quantum engine, quantum thrust, quantomobile, quantum quarrying lift-and-transport machinery, force balance, quarrying.

Introduction

In a number of papers (Kotikov, 2018a, 2018b, 2018c, 2018d, 2019a, 2019b, 2019c, 2019d), the author addressed the prospects of using the methods of energy extraction from the physical vacuum in the transport industry. The introduction of quantum thrust in automobiles will result in the appearance of a new type of transport — quantomobiles.

The author also considered the possibility of replacing lift-and-transport machinery at terminals and warehouses with universal quantum lift-and-transport machinery (QLTM) by introducing quantum thrust (Kotikov, 2019e). The possibility of energy extraction from the physical vacuum, uncovered in case of potential mastering of the foundations of the theory of Superunification (Leonov, 2002, 2010, 2018), will change the motion mechanics and the pattern of using lift-and-transport machinery if those are equipped with quantum engines (QEs).

Unlike ICEs and electric motors, QEs directly generate thrust, which can be applied to the vehicle/machine/wagon body (Brandenburg, 2017, Fetta, 2014, Frolov, 2017, Tajmar et al., 2007). This creates prerequisites for the appearance of quantum lift-and-transport machinery (QLTM) able to lift off the bearing surface (overcoming gravity) and transport cargo hovered over such surface horizontally or at an angle (Kotikov, 2019e).

Acknowledging that the addressed ideas are hypothetical and the proposed design solutions are quite distant in time, we will consider the possibility and prospects of using QLTM in quarrying technology.

Purpose and tasks of the study

The purpose of the study is to develop a conceptual foundation and a working hypothesis for the operation of lift-and-transport machinery with quantum thrust used for quarrying (Quantum Quarrying Lift-and-Transport

DOI: 10.23968/2500-0055-2020-5-2-46-56

Machinery (QQLTM)) as an idea-driven basis for the modernization of quarrying technology.

To achieve the purpose, it is required to solve the following tasks:

- to describe challenges of rock transportation from the pit bottom to the upper levels;
- to assess specific features and capabilities of QE thrust to ensure lift-and-transport operations related to quarrying;
- to build a mathematical model of QQLTM force balance and motion;
- to analyze numerical examples describing rock transportation with the use of QQLTM;
- to summarize the results of the study and offer recommendations for further studies in this area.

Challenges of rock transportation from the pit bottom to the upper levels

Let us describe general aspects of mining technology and corresponding issues using data on the Lebedinsky Mining and Processing Plant (Lebedinsky GOK) located in the area of the Kursk Magnetic Anomaly (Alekseev, 2012, Vasiliev, 2016, Yandex Zen, 2018a, 2018b). A general view of the Lebedinsky GOK quarry is given in Figure 1.

Figure 1. Lebedinsky GOK quarry (https://cont.ws/uploads/pic/2018/10/a65.jpg).

The amount of ferruginous quartzites annually mined at the Lebedinsky GOK is more than 50 mln t. The open pit has a length of 5 km, a width of 3 km, and a depth of 350 m (Vasiliev, 2016).

After blasting operations and destruction of a rock mass, excavators, front loaders, and bulldozers load ore-bearing rock into dump trucks, which transport and unload it at transfer stations at higher quarry levels. Then, excavators load ore on trains. A mining and processing plant and stockpiles are the final destinations of minerals.

The distance between the levels at the Lebedinsky GOK quarry is 15 m. The number of quarry benches is about 20.

Figure 2 shows a scheme of operations in quarries of such a type. The yellow (Euclidean) line reflects the relationship between the truck loading area at the pit bottom (AB level) and the truck unloading area at the transfer station level (CD level). Trucks move along the expanding spiral of temporary roads (berms) on the lower slope. The route length may be as high as 5 km. The speed of trucks is 10–15 km/h.

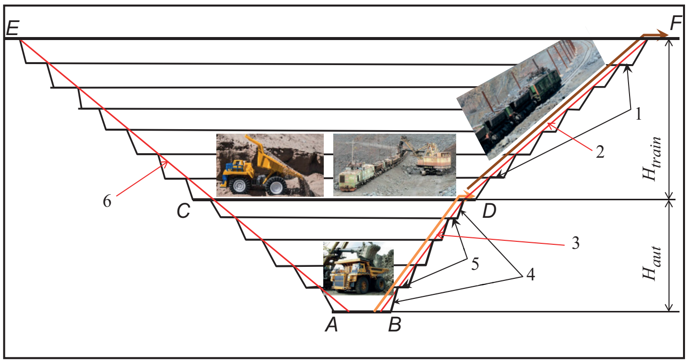

Figure 2. Quarry components and organization of work in quarries: 1 — berms of the upper levels; 2 — slope of the upper highwall; 3 — slope of the lower highwall; 4 – bench faces; 5 — berms of the lower levels; 6 — slope of the spoil bank; H_{aut} — height of the lower slope (road-served); H_{train} — height of the upper slope (rail-served); AB, CD, EF — lower (bottom), intermediate (transfer), and upper (output) levels, respectively.

On the upper slope (in the CEFD space), the rock is transported by railway: traction units including electric locomotives, motor-coach trains, and non-motorized wagons (dumpcarts). Power is supplied from a grid expanding with the railway tracks into the depth of the quarry. Traction units are loaded at the CD level transfer station by excavators. Obviously, such a transfer slows down rock transportation.

The brown (Euclidean) line reflects the relationship between the traction unit loading area at the transfer station (CD level) and the traction unit unloading area at the upper EF level (mining and processing plants for ore-bearing rock or stockpiles for waste rock). Traction units move along the railway network on the upper slope and in adjacent areas. The route length in the CEFD space on the upper slope can be as high as 20 km. The speed of trains moving along the berms of the upper slope is around 15 km/h.

As we can see, the technology of rock transportation from the lower (bottom) to the upper level is quite energy-consuming. Even if we consider only the process described, we should take into account truck loading, movement of trucks on uphill winding roads (berms) for 1–5 km (although, along a Euclidean line, the distance is just 80–100 m), unloading at the CD level storage area, and their movement back. We also should factor in train loading, movement of trains along the temporary low-quality railway network for 5–20 km (although, along a Euclidean line, the distance is just 200–300 m), their movement back, and maneuvering. Material and energy consumption aimed to ensure transportation is rather significant since it is required to lay and maintain roads on the lower slope, ensure the continuous expansion of the railway network and its power supply on the upper slope.

The production of the machinery mentioned is also material- and energy-consuming since the process of design development requires significant expenditures.

As for the quarry operations with the use of automobiles, the main transportation workload falls on 25 large BelAZ-75131 dump trucks (Trucks Review 2019, Vasiliev, 2016). Electric excavators load the dump trucks with rock. The bucket capacity of EKG-8Sh, EKG-10, EKG-11i and EKG-12.5 excavators is 8, 10, 11 and 12.5 m^3, respectively. A dump truck can be filled in 6–10 cycles.

The trucks haul away 40,000 tons of ore and 5000–6000 m^3 of overburden rocks per shift. 120,000 tons of rock mass can be transported per day. For instance, the average monthly excavation volume per BelAZ-75131 can reach 147,000 tons, the average monthly distance covered by a loaded truck — 18,000 km, and the average monthly cargo turnover — 1,720,000 t·km (Vasiliev, 2016).

Based on the foregoing, we can distinguish the following challenges related to rock transportation from the pit bottom to the upper levels (both for the Lebedinsky GOK quarry and other quarries worldwide): 1) low speed of rock transportation; 2) high energy consumption in terms of individual components and the rock transportation process in general; 3) high material intensity in terms of transportation facilities and maintenance of their operation.

These issues can be addressed with the introduction of QQLTM considered in this paper.

Methods

Mathematical model of QQLTM force balance and motion

Thrust vector decomposition

The three-dimensional thrust vector can be decomposed into unit vectors (Leonov, 2018, Kotikov, 2019c, 2019d):

$$\boldsymbol{F_T} = \boldsymbol{F_{Tx}} + \boldsymbol{F_{Ty}} + \boldsymbol{F_{Tz}} \quad (1)$$

Within the framework of the task considered, which is to describe the longitudinal (course) motion of QQLTM in the plane of pitch angle β, equation (1) takes the following form:

$$\boldsymbol{F_T} = \boldsymbol{F_{Tx}} + \boldsymbol{F_{Tz}} \quad (2)$$

The scalar form of this equation is as follows:

$$\sqrt{F_{Tx}^2 + F_{Tz}^2} \quad (3)$$

Graphically, it is given in Figure 3.

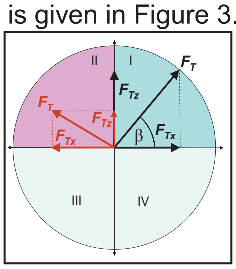

Figure 3. $\boldsymbol{F_T}$ thrust decomposition into the horizontal ($\boldsymbol{F_{Tx}}$) and vertical ($\boldsymbol{F_{Tz}}$) components: β — $\boldsymbol{F_T}$ thrust angle relative to the horizon

Equations (2) and (3) are general initial equations for the calculation of QQLTM motion both in vertical (with the takeoff of cargo from the bottom surface and its lifting) and horizontal direction (transportation of cargo within the level), as well as in case of combined motion along inclined trajectories.

Vectors located on the vertical axis correspond to the true vertical motion of QQLTM (Figure 3). The first (blue) quadrant of the circle formed by the thrust vector tip corresponds to the uniformly accelerating longitudinal motion of QQLTM (with the realization of direct thrust). The second (pink) quadrant corresponds to the longitudinal braking and reverse modes.

QQLTM and ground LTM force balance analyses differ. This is due to the fact that the force balance and motion equation involves new entities and physical quantities, which manifest when vertical forces (gravity, hovering, wind resistance to vertical motion, vertical accelerations) are taken into account.

QQLTM force balance equation and motion equations based on it

Let us modify the force balance equation for a vehicle with a QE, derived by the author earlier (Kotikov, 2019c, 2019d, 2019e), and use it as a working equation:

$$F_T^2 = F_{Tx}^2 + F_{Tz}^2 = \left(P_{w.x} + P_{j.x}\right)^2 + \left(P_{w.z} + P_{j.z} + P_g\right)^2 =$$
$$\left(k_{w.x} \cdot S_{front} \cdot V_x^2 + \frac{G_{QQLTM}}{g} a_x\right)^2 +$$
$$\left(\left(k_{w.z} \cdot S_{plan} \cdot V_z^2 + \frac{G_{QQLTM}}{g} a_z\right)\Big|_{F_{Tz} > G_{QQLTM}} + \min(F_{Tz}, G_{QQLTM})\right)^2, \quad (4)$$

where:

F_T, F_{Tx}, F_{Tz} — thrust and its coordinate components, respectively, N;

$P_{w.x}$ — wind resistance to the horizontal motion, N;

$P_{j.x}$ — a force of resistance to horizontal acceleration, N;

$P_{w.z}$ — wind resistance to the vertical motion, N;

$P_{j.z}$ — a force of resistance to vertical acceleration, N;

$P_g = G_{QQLTM}$ — a part of the vertical component of thrust used to neutralize the gravity of loaded QQLTM being transported, N;

V_x — the current velocity of QQLTM longitudinal (course) motion, m/s;

G_{QQLTM} — weight of QQLTM (loaded or unloaded as the case may be), N;

$k_{w.x}$ — QQLTM horizontal (longitudinal) wind shape coefficient, N · s^2/m^4;

S_{front} — the frontage area of QQLTM, m^2;

V_w — the longitudinal velocity of QQLTM relative to the wind (in the present study, $V_w = V_x$), m/s;

g — gravitational acceleration, m/s^2;

a_x — longitudinal acceleration of loaded QQLTM, m/s^2;

$k_{w.z}$ — QQLTM vertical wind shape coefficient, N · s^2/m^4;

S_{plan} — the area of QQLTM in plan view, m^2;

DOI: 10.23968/2500-0055-2020-5-2-46-56

V_z — vertical motion velocity of QQLTM, m/s;
a_z — vertical acceleration of QQLTM, m/s^2.

It should be noted that $G_{QQLTM} = G_{QQLTM.0} + G_c$, where $G_{QQLTM.0}$ is the weight of unloaded QQLTM and G_c is the weight of transported cargo with the package.

Equation (4) represents a generalized expression of QQLTM force balance that comprises the following typical cases of QQLTM operation:

1) initial state of QQLTM with cargo (at the pit bottom), $F_{Tz} = 0$;
2) transition mode of partial hovering of loaded QQLTM, when $0 < F_{Tz} < G_{QQLTM}$;
3) boundary mode — with zero contact between cargo and the bearing surface (without QQLTM takeoff), when $F_{Tz} = G_{QQLTM}$;
4) vertical takeoff of QQLTM with acceleration (at $F_{Tz} > G_{QQLTM}$);
5) vertical takeoff of QQLTM with deceleration (at $F_{Tz} < G_{QQLTM}$);
6) vertical landing with downward-directed acceleration ($F_{Tz} < G_{QQLTM}$);
7) vertical landing with downward-directed deceleration ($F_{Tz} > G_{QQLTM}$);
8) mode of final fixation of QQLTM (or rock unloading).

Equation (4) has the following distinctive feature: the "min(F_{Tz}, G_{QQLTM})" equation term represents a force to overcome gravity created by the mass of loaded QQLTM: partially — when at $F_{Tz} \le G_{QQLTM}$ it is not physically possible for QQLTM to take off, or at $F_{Tz} > G_{QQLTM}$ — when gravity is overcome completely, it is possible for QQLTM to take off the bearing surface due to the remaining force $R_{FTz} = F_{Tz} - G_{QQLTM}$.

In one of his papers (Kotikov, 2019e), the author generated several equations for individual cases and QLTM motion modes. Some of them can be of use here:

The velocity of steady motion in a horizontal plane V_x:

$$V_x = \sqrt{\frac{F_{Tx}}{k_{w.x} \cdot S_{front}}} \tag{5}$$

The longitudinal acceleration of QQLTM in the mode of full hovering (at $F_{Tz} = G_{QQLTM}$):

$$a_x = \frac{g}{G_{QQLTM}}(F_{Tx} - k_{w.x} \cdot S_{front} \cdot V_x^2) \tag{6}$$

The maximum possible longitudinal velocity of hovering QQLTM can be determined by setting $a_x = 0$:

$$V_{x.\max} = \sqrt{F_{Tx} / k_{w.x} \cdot S_{front}} \tag{7}$$

The longitudinal acceleration at the initial moment of longitudinal motion of hovering QQLTM can be determined by setting $V_x = 0$:

$$a_x = \frac{F_{Tx} \cdot g}{G_{QQLTM}} \tag{8}$$

The vertical acceleration of QQLTM (at $F_{Tz} > G_{QQLTM}$):

$$a_z = \frac{g}{G_{QQLTM}}(F_{Tz} - G_{QQLTM} - k_{w.z} \cdot S_{plan} \cdot V_z^2) \tag{9}$$

Setting $V_z = 0$, it is possible to calculate the vertical acceleration at the initial moment of QQLTM ascent:

$$a_z = \frac{g}{G_{QQLTM}}(F_{Tz} - G_{QQLTM}) \tag{10}$$

The analysis based on equations (3)...(10) can be complemented with corresponding graphical models. We used Maple software to program the mentioned equations with different graphical representations (Kotikov, 2019d).

Comparative analysis of rock transportation time

We will evaluate the transportation time (and later — energy consumption) with regard to the batch of rock with a mass of 130 t, starting from the moment when a loaded vehicle started moving (at first, BelAZ-75131, and then QQLTM). Let us record the time when the cargo is delivered to the CD level transfer station.

Then we will calculate the transportation time (and later — energy consumption) with regard to the batch of rock with a mass of 130 t to the upper EF level, starting from the moment when a loaded vehicle started moving at the pit bottom and ending with unloading at the EF level. In this case, the cargo with a mass of 130 t is transported with standard vehicles in three stages: transportation with a BelAZ-75131 with unloading at the CD level, loading with an EKG-8i excavator on a train, rail delivery to the EF level. If the cargo is transported with QQLTM, the delivery will not be interrupted.

Transportation from the pit bottom to the transfer station with a dump truck

Let us consider the option with the use of standard technologies. Even if the loaded BelAZ-75131 moves along the berms of the lower slope at a maximum allowable speed of 15 km/h (with no regard for deceleration on turns and when avoiding obstacles), in the case of the statistically average route length of 2 km, the transportation time will be 8 min.

Transportation from the pit bottom to the upper level with two types of standard vehicles

After the delivery by road (8 min mentioned), the cargo is unloaded (2 min) and held at the transfer station to be consolidated with cargo from other trucks and then loaded on a traction train (30 min). The time of transportation by train is 42 min (Allbest, 2019). Therefore, the total transportation time is 82 min.

Since the train capacity is 1040 t (Allbest, 2019, Vasiliev, 2016), then eight rock batches with a mass of 130 t each can be loaded on a train. If we reduce the rail transportation time (30 + 42 = 72 min) to one batch with a mass of 130 t, we will obtain 72/8 = 9 min. Then the reduced time for the transportation of 130 t of rock from the pit bottom to the upper level is 8 + 2 + 9 = 19 min.

Transportation from the pit bottom to the transfer station with QQLTM

Let us consider the option when automobiles are replaced by quantum lift-and-transport machinery

(QQLTM) used at the lower levels of a quarry. Instead of rock transportation with dump trucks along the winding berms of the lower levels (see item 5 in Figure 2), we will consider rock delivery to the transfer station with QQLTM along rectangular trajectory 8 (Figure 4).

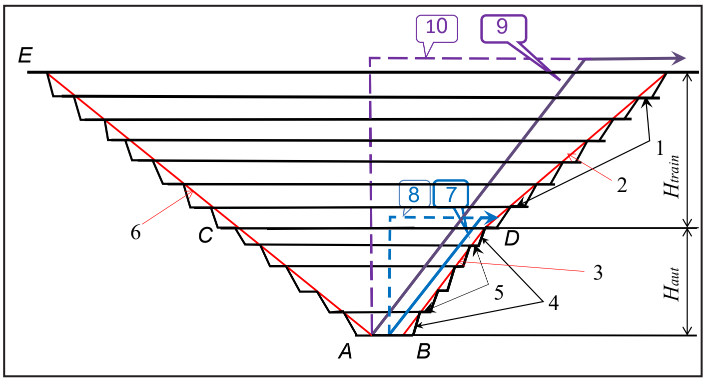

Figure 4. Quarry components and organization of QQLTM motion in quarries: 1 — berms of the upper levels; 2 — slope of the upper highwall; 3 — slope of the lower highwall; 4 — bench faces; 5 — berms of the lower levels; 6 — slope of the spoil bank; 7 — inclined trajectory of QQLTM motion to the transfer station; 8 — rectangular trajectory of QQLTM motion to the transfer station; 9 — inclined trajectory of QQLTM motion to the upper level; 10 — rectangular trajectory of QQLTM motion to the upper level; H_{aut} — height of the lower slope; H_{train} — height of the upper slope.

To substitute BelAZ-75131 for one-time transportation of the batch of rock with a mass of 130 t, we use QQLTM with an own mass of 40 t (30 t — the mass of the load-bearing body (Sibdepo, 2010) + 10 t — the mass of the QE, bearing, fixing, joining and other structural elements (this value is determined by expert estimation)). Then the mass of the loaded machine is 170 t (weight of ≈1700 kN).

It is easy to imagine that QQLTM used for rock transportation can be quickly assembled from two parts: a load-bearing body and a spreader with a QE.

The load-bearing body is designed to accommodate rock. The top of the body is open so that it would be possible for excavators to load the machine with rock at the pit bottom. When the body is filled with rock, the spreader approaches it from above, and the QQLTM structure locks (obviously, it has the required fixing and joining elements). The loaded QQLTM sets off, being lifted with the vertical pulling force of thrust F_{Tz} generated in the QE and applied to the load-bearing body. In the unloading area at the CD level, the QQLTM cargo can be unloaded on the ground or a train wagon. For that purpose, the QQLTM design shall include a dump unloading system (with the tipping axle on one of the body sides). During unloading, the thrust vector shall decrease according to changes in the QQLTM mass. The load-bearing body can be placed on the ground or a train wagon, unlocked from the spreader, and then locked again to return to the pit bottom for another batch of rock.

Let us assume that the upper part of the QQLTM structure is represented by a spreader (like a container spreader (Alfa Group, 2019, Container Spreaders. Com, 2019) but with a larger size and mass) equipped with a QE. We will set other characteristics of loaded QQLTM, required for modeling as per equation (4), by expert estimation: $k_{w.x}$ = 0.8 N×s²/m⁴; S_{front} = 10 m²; $k_{w.z}$ = 0.9 N×s²/m⁴; S_{plan} = 20 m².

By analogy with the substantiation of a case with container transportation (Kotikov, 2019e), we will take the value of maximum thrust as exceeding the total weight of a lift-and-transport machine by 5–6%, i.e. 1800 kN.

Figure 5 shows representations of the QQLTM thrust characteristics: maximum vertical thrust $F_{Tz.acc}$ enabling QQLTM ascent with acceleration along the verticals of rectangular trajectories 8 and 10 (Figure 4), as well as maximum but inclined thrusts $F_{T.acc}$ and $F_{T.dec}$ enabling motion of the hovering QQLTM along the horizontals of rectangular trajectories 8 and 10 (Figure 4). Angles β_{acc} and β_{dec} are equal to 70.8°. $F_{Tz.acc}$ = 1800 kN, $F_{Tz'dec}$ = 1600 kN. $F_{Tz.hov}$ = G_{QQLTM} = 1700 kN, $F_{Tx.acc}$ = –$F_{Tx.dec}$ = 592 kN.

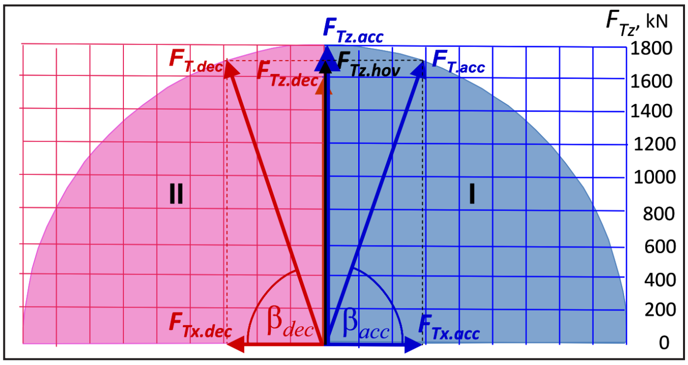

Figure 5. QQLTM thrust characteristics and the correspondence between the thrust representations and motion modes: $F_{Tz.acc}$ — vertical ascent with acceleration (or vertical descent with deceleration); $F_{Tz.hov}$ — hovering; $F_{Tz.dec}$ — vertical ascent with deceleration (or vertical descent with acceleration); $F_{T.acc}$ — horizontal acceleration; $F_{T.dec}$ — horizontal deceleration; $F_{Tx.acc}$ — a horizontal component of accelerating thrust; $F_{Tx.dec}$ — a horizontal component of decelerating thrust; β_{acc} and β_{dec} — inclination angles of accelerating and decelerating thrusts, respectively.

Let us assume that rectangular trajectory 8 for the motion of loaded QQLTM is determined as follows (Figure 4):

1) vertical ascent to a height of 78 m (3 m higher than the CD level): with acceleration and then with deceleration to V_z = 0; 2) horizontal motion for 90 m: uniformly accelerated and uniformly decelerated to V_x = 0; 3) bin unloading.

1. Vertical acceleration is conditioned by the fact that the value of vertical thrust exceeds the QQLTM weight (i.e. 1800 – 1700 = 100 kN, see Figure 5):

$$a_z = \frac{g}{G_{QQLTM}}(F_{Tz.acc} - G_{QQLTM}) =$$

$$9.8 * (1800 - 1700)/1700 = 0.576 \text{ m/s}^2$$

(which can be accepted).

Then the ascent time to a height of 78/2 = 39 m: t = sqrt(2h/a_z) = sqrt(2*39/0.576) = 11.6 s.

Vertical velocity (at the moment when a height of 39 m is reached) V_z = sqrt(2a_z*h) = sqrt(2*0.576*39) = 6.7 m/s (which also can be accepted).

DOI: 10.23968/2500-0055-2020-5-2-46-56

Let us calculate the value of wind resistance at this speed:

$P_{w.z}=k_{wz} \cdot S_{PLAN} \cdot V_z^2 =$ 0.9 N×s²/m⁴ * 20 m² * 6.72 m²/s² = 808 N = 0.808 kN. Thus, we obtain a rather small value (0.8%) (when compared with the excess vertical thrust). Therefore, we can neglect wind resistance at such QQLTM speeds.

Let us assume that QQLTM decelerates in a mirror-like manner with respect to acceleration, now with an acceleration of –0.576 m/s². This is possible due to the fact that the value of vertical thrust falls short of the QQLTM weight (i.e. 1600 – 1700 = –100 kN, see Figure 5):

$$a_z = \frac{g}{G_{QQLTM}}(F_{Tz.dec} - G_{QQLTM}) =$$

$$9.8 * (1600 - 1700)/1700 = -0.576 \text{ m/s}^2.$$

Then the total time of ascent to a height of 78 m: t = 11.6 * 2 = 23.2 s.

2. The horizontal motion at the section of 90 m similarly comprises such stages as acceleration and deceleration.

Acceleration:

$$a_x = \frac{F_{Tx.acc} \cdot g}{G_{QQLTM}} =$$

$$592 \text{ kN} * 9.8 \text{ m/s}^2 / 1700 \text{ kN} = 3.41 \text{ m/s}^2.$$

The acceleration time at the section of 45 m:
t = sqrt($2l/a_x$) = sqrt(2*45/3.41) = 5.14 s.

Let us assume that QQLTM decelerates in a mirror-like manner with respect to acceleration, now with an acceleration of –3.41 m/s². Then the total time of horizontal motion at the section of 90 m: t = 5.14 * 2 ≈ 10.3 s.

The total time of rock transportation from the pit bottom to the transfer station at the CD level: t = 23.2 + 10.3 = 33.5 s.

Let us compare this result with the time of transportation with a BelAZ-75131 truck. When it moves along the berms of the lower slope at a speed of 15 km/h and the statistically average route length is 2 km, the transportation time will be 8 min. Therefore, the time of transportation with QQLTM is 480 s / 33.5 s =14 times lower than the time of transportation with a truck.

Transportation from the pit bottom to the upper EF level with QQLTM

Let us assume that rectangular trajectory 10 for the motion of loaded QQLTM is determined as follows (Figure 4):

1) vertical ascent to a height of 350 m: with acceleration and then with deceleration to V_z = 0;

2) horizontal motion for 500 m: uniformly accelerated and uniformly decelerated to V_x = 0; 3) bin unloading.

1. Vertical acceleration is conditioned by the fact that the value of vertical thrust exceeds the QQLTM weight (i.e. 1800 – 1700 = 100 kN):

$$a_z = \frac{g}{G_{QQLTM}}(F_{Tz.acc} - G_{QQLTM}) =$$

$$9.8 (1800 - 1700)/1700 = 0.576 \text{ m/s}^2$$

(which can be accepted).

Then the ascent time to a height of 350/2 = 175 m: t = sqrt($2h/a_z$) = sqrt(2*175/0.576) = 24.65 s.

Vertical velocity (at the moment when a height of 175 m is reached) V_z = sqrt($2a_z*h$) = sqrt(2*0.576*175) = 14.2 m/s (which also can be accepted).

Let us calculate the value of wind resistance at this speed:

$$P_{w.z} = k_{w.z} \cdot S_{plan} \cdot V_z^2 = 0.9 \text{ N}\cdot\text{s}^2/\text{m}^4 * 20 \text{ m}^2 *$$

$$* 14.2^2 \text{ m}^2/\text{s}^2 = 3629 \text{ N} = 3.629 \text{ kN}.$$

Thus, we obtain a rather small value (3.6%) (when compared with the excess vertical thrust). Therefore, we can neglect wind resistance at such QQLTM speed.

Let us assume that QQLTM decelerates in a mirror-like manner with respect to acceleration, now with an acceleration of –0.576 m/s². Then the total time of ascent to a height of 350 m: t = 24.65 * 2 = 49.3 s.

2. The horizontal motion at the section of 500 m similarly comprises such stages as acceleration and deceleration.

Acceleration (quadrant I, Figure 5):

$$a_x = \frac{F_{Tx.acc} \cdot g}{G_{QQLTM}} =$$

$$592 \text{ kN} * 9.8 \text{ m/s}^2 / 1700 \text{ kN} = 3.41 \text{ m/s}^2.$$

The acceleration time at the section of 250 m: t = sqrt($2l/a_x$) = sqrt(2*250/3.41) = 12.1 s.

Let us assume that QQLTM decelerates (quadrant II) in a mirror-like manner with respect to acceleration, now with an acceleration of –3.41 m/s². Then the total time of horizontal motion at the section of 500 m: t = 12.1 * 2 = 24.2 s.

The total time of rock transportation from the pit bottom to the upper EF level:

t = 49.3 + 24.2 = 73.5 s ≈ 1.3 min.

Let us compare this result with the total time required to transport 130 t of rock with two types of standard vehicles, involving transshipment (the reduced time was 19 min). We can state that cargo can be transported with QQLTM 19/1.3 ≈ 14 times faster.

Comparative analysis of energy consumption for rock transportation

Transportation from the pit bottom to the transfer station with a BelAZ dump truck

Just to be on the safe side, let us determine energy consumption for rock transportation with a BelAZ-75131 dump truck in two ways: 1) considering standard pre-determined fuel consumption for transportation (in g/(t-km)); 2) considering statistical fuel consumption required to lift 1 t of rock to a height of 1 m.

Method 1. According to Lel' et al. (2017), standard values of fuel consumption by dump trucks can be presented in the form of a nomogram in Figure 6.

In our case, N_a = f (L, м) = f (2.0; 3.0) ≈ 100 g/t-km. If 130 t of rock are transported for 2 km, then diesel fuel consumption will be 100 g/t-km * 130 t * 2 km = 26 kg.

Method 2. According to Voroshilov and Lel' (2009), the relationship between the specific fuel consumption by BelAZ-7519 (similar to BelAZ-55131 in terms of specifications) when hill-climbing (P) and inclination (i) and rolling resistance (ω_0) can be presented in the form of a nomogram in Figure 7.

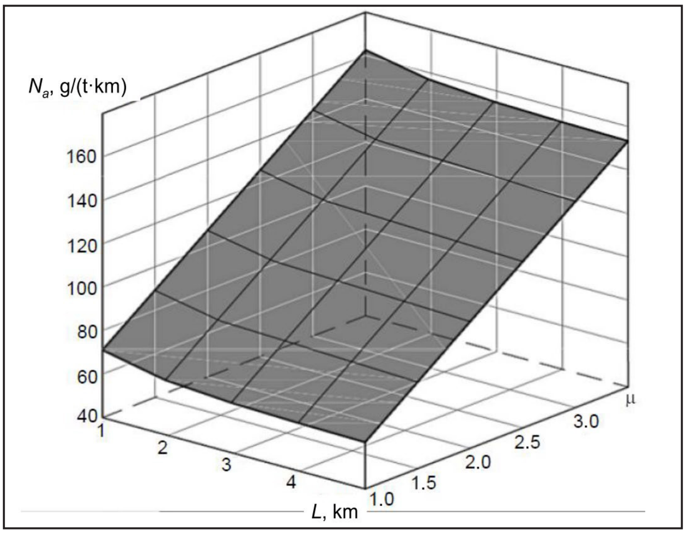

Figure 6. Standard values of fuel consumption by a dump truck N_a, g/(t·km) vs. transportation distance *L* and route complexity factor м.

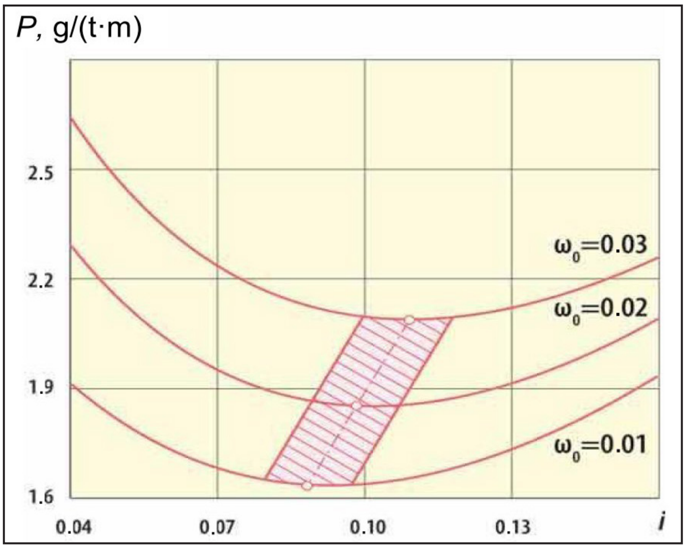

Figure 7. Specific fuel consumption by BelAZ-7519 when hill-climbing (P) vs. inclination (i) and rolling resistance (ω_0).

In our case, inclination *i* = 80 m/2000 m = 0.04. Then, for ω_0 = 0.03, P = 2.7 g/t-m. To transport 130 t of rock to a height of 80 m, diesel fuel in the amount of 2.7 g/t-m * 130t * 80 m = 26.325 kg will be required.

The calculation results are quite similar. Let us settle on the value of 26 kg and convert that to MJ: E_{Aut} = 26 kg * 42.7 MJ/kg =1110 MJ.

Transportation from the pit bottom to the upper level with two types of standard vehicles

On the CD level, rock is loaded on train wagons by EKG-8i excavators with a standard specific consumption of 1.11 kWh/m^3 (Vunivere.ru, 2019).

At the iron ore bulk density of 2 t/m^3 (Engineering reference book. DPVA.ru tables, 2019), rock with a mass of 130 t occupies a volume of 65 m^3. Therefore, during the loading of 130 t of ore on a train using EKG-8i excavators, energy consumption amounts to 65 m^3 * 1.11 kWh/m^3 = 72.15 kWh = 259,740 kJ ≈ 260 MJ.

Let us determine energy consumption for rail transportation based on data (Voroshilov and Lel', 2009) on energy consumption required to lift 1 t of rock to a height of 1 m.

Specific energy consumption of railway transport required to transport rock mass from quarries is 0.009–0.012 kWh/t·m (Voroshilov and Lel', 2009). Let us take this value equal to 0.01 kWh/t·m. Then, to deliver 130 t of ore to a height of 270 m, energy in the amount of 0.01 * 130 * 270 = 351 kWh ≈ 1264 MJ will be required.

Total energy consumption for rock transportation from the pit bottom to the upper level with two types of standard vehicles, involving transshipment, will amount to 1110 + 260 + 1264 = 2634 MJ.

Transportation from the pit bottom to the transfer station with QQLTM

When rock is transported with QQLTM, the energy of the physical vacuum is used to generate the bearing thrust vector.

The route consists of vertical and horizontal components: *L* = 78 + 90 = 168 m. The value of the thrust vector at the section of ascent with acceleration (39 m) $F_{Tz\cdot acc}$ = 1800 kN, at the section of ascent with deceleration (39 m) — $F_{Tz.dec}$ = 1600 kN, at horizontal sections — F_T = 1800 kN (only its direction changes when switching from acceleration to deceleration). The work done is as follows: A = 1800 kN * 39 m + 1600 kN * 39 m + 1800 kN * 90 m = 294,600 kJ.

It shall be particularly noted that despite the fact that horizontal motion is initiated by the horizontal component of thrust F_T, i.e. force F_{Tx} = 592 kN, the corresponding work done at the horizontal section of 90 m is determined by force F_T = 1800 kN, since energy of motion here is associated with the simultaneous gravity overcoming (accompanied by energy consumption) and QQLTM support at a height within the entire section of horizontal motion.

Since 10% of power flow (for the purposes of discussion and with account for the results of studies (Leonov, 2010)) are spent for QE operation related to the extraction of energy from the physical vacuum and thrust generation, energy consumption will amount to the following: E_{QQLTM} = *A* * 1.1 = 324,060 kJ ≈ 324 MJ.

Let us compare the values of energy consumption: E_{Aut} / E_{QQLTM} = 1110 MJ / 324 MJ = 3.43. In other words, during transportation with QQLTM, energy consumption is 3.43 times less.

Transportation from the pit bottom to the upper level with QQLTM

The route consists of vertical and horizontal components: *L* = 350 + 500 = 850 m. The value of the thrust vector at the section of ascent with acceleration (175 m) $F_{Tz.acc}$ = 1800 kN, at the section of ascent with

DOI: 10.23968/2500-0055-2020-5-2-46-56

deceleration (175m) — $F_{Tz.dec}$ = 1600 kN, at horizontal sections — F_T = 1800 kN (only its direction changes when switching from acceleration to deceleration). The work done is as follows: A = 1800 kN * 175 m + 1600 kN * 175 m + 1800 kN * 500 m = 1,495,000 kJ = 1495 MJ.

Since 10% of power flow are spent for QE operation, energy consumption will amount to the following: E_{QQLTM} = A * 1.1 = 1,644,500 kJ ≈ 1645 MJ.

Let us compare the values of energy consumption: $E_{Aut+Train}$ / E_{QQLTM} = 2634 MJ / 1645 MJ = 1.6. In other words, during transportation with QQLTM, energy consumption is 1.6 times less.

Discussion

The calculation results are summarized in Table 1.

Table 1. Results of the comparative analysis for two methods of rock transportation.

Transportation area	Transportation time, min		Vehicle substitution effect multiplicity, times	Energy consumption, MJ		Vehicle substitution effect multiplicity, times
	Standard transport	QQLTM		Standard transport	QQLTM	
Lower slopes	8	0.56	14	1110	324	3.43
All slopes (total)	19	1.3	14	2634	1645	1.6

It can be seen that, with the use of QQLTM, the time required to deliver rock from the pit bottom can be decreased by an order and energy consumption can be reduced by 1.5–3 times.

Despite the fact that the example of QQLTM motion along the rectangular trajectory with sudden changes in the nature of motion (switching from vertical motion to horizontal, rough thrust vector switching, and, as a consequence, rough changes in QQLTM accelerations) is rather simple, we have managed to get an overview of QQLTM motion.

Sure enough, QQLTM motion can be more complex and elegant, with inclined ascents and descents, maneuvering over the facilities of a quarry, consideration of the difference between ascent and descent stages as well as their specifics (in contrast with their “mirror-like” nature).

Transportation operations at a mining and processing plant require at least a half of total economic expenditures and energy consumption. Besides, since the quarry space intended for transportation is tight and challenging, rock excavation is carried out rather slowly. The continuous process of preparing road and railway vehicles for rock transportation is also time- and material-consuming. QQLTM can reduce all the mentioned expenditures significantly: first, due to the possibility of using the air space of a quarry for transportation; second, due to the elimination of labor-consuming road works; and third, due to the substitution of material-consuming road-building machinery, transport equipment, and power supply facilities.

In case of mass use of QQLTM, dispatching can be performed with the distribution of trajectories in a 3D space, where all QQLTM units are unified by a single purpose — prompt delivery of rock to destination points.

QQLTM can be introduced by stages: at first, trucks (ABCD in Figures 2 and 4), and then railway transport (CDEF) will be substituted. It is possible that in the long run rock transportation from the pit bottom directly to mining and processing plants as wells as stockpiles will be carried out by joint groups of unified QQLTM controlled by automatic control systems.

With no trucks and trains on the slopes of a quarry, it will be possible to perform mining development not only in the pit bottom but on the slopes as well. This will speed up quarrying in general. It is likely that the new methods of extracting energy from the physical vacuum will result in the modernization of equipment and technologies used for mining development.

The aspects discussed will be elaborated in detail with the development of quantum machinery.

Conclusion

The study shows that given the actual realization of the idea and implementation of the principles of non-fuel energy production based on the extraction of energy from the physical vacuum, the presented QQLTM concept and its use in quarrying technology are rather sounded. However, the actual realization of the QQLTM concept will require significant research and implementation efforts of the scientific and technical community in the area of non-fuel energy production, which is currently in its infancy. In the course of its development, materials, equipment, and technologies will improve as well, which will determine the difference of future QQLTM from the hypothetical machine and its use described in this paper.

As for future global exploration and implementation efforts in the extraction of energy from the physical vacuum, if we limit the range of problems by the transport industry, then the solution of the QE development problem will play a key role in a breakthrough to new technologies. In the short term, it will be necessary to accelerate efforts in searching for required QE designs and the technological capabilities of their manufacturing.

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КВАНТОВАЯ КАРЬЕРНАЯ ПОДЪЕМНО-ТРАНСПОРТНАЯ МАШИНА

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Аннотация

Освоение способов извлечения энергии из физического вакуума и внедрение их в инженерную деятельность изменит механику движения и характер использования подъемно-транспортных средств, при установке на них квантовых двигателей (КвД). **Цель.** Формирование концепции и рабочей гипотезы функционирования квантовой карьерной подъемно-транспортной машины (QQLTM). **Проблемы**. Рассматриваются проблемы доставки горной породы со дна карьера на верхние уровни. **Методы.** Разложение вектора траста на ортогональные компоненты. Формирование уравнения силового баланса и движения QQLTM. Определение характерных режимов QQLTM. Расчетные и графоаналитические исследования. **Результаты.** Представлены результаты вычислений времени перемещения и энергозатрат по переносу горной породы на конкретных примерах движения груженого QQLTM со дна карьера на перегрузочную площадку и верхний горизонт карьера. **Обсуждение.** Существующие комплексы автомобильных, железнодорожных транспортных средств и погрузочно-разгрузочной техники могут быть заменены группами транспортирующих машин с КвД в их конструкциях – QQLTM. Это позволит существенно совершенствовать технологию разработки карьеров (quarrying), внедрить непрерывное перемещение груза без перегрузки с одного вида транспорта на другой и значительно снизить энергозатраты, уровень материальных и трудозатрат.

Ключевые слова

Квантовый двигатель, квантовая тяга, квантомобиль, квантовая карьерная подъемно-транспортная машина, силовой баланс, разработка карьера.