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INVESTIGATING THE CORROSION INITIATION PROCESS IN REINFORCED CONCRETE STRUCTURES UNDER THE IMPACT OF CLIMATE CHANGE

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Abstract
Introduction: Climate change (temperature rise and sea level rise) has a considerable influence on the behavior of concrete structures over time. All concrete degradation processes are connected to climate variables and the effects of climate change. The RCP8.5 (Representative Concentration Pathway) scenario, which is part of the report on climate change and level rise scenarios for Vietnam, predicts that the beginning of the 21st century will see an average annual increase in temperature between 0.8 and 1.1°C. In the mid-21st century, the temperature will likely increase by 1.8–2.3°C, with the temperature in the north likely increasing by 2.0–2.3°C and in the south by 1.8–1.9°C. In marine environments, the degradation of concrete structures can occur rapidly due to chloride-induced reinforcement corrosion. Furthermore, sea level rise is going to reduce the distance from the coastline to the structures and lead to increased surface chloride concentration. **Methods:** The evaluation of chloride penetration was based on the ASTM C1202 test (ASTM, 2012). The cylinder specimens (d = 100 mm, h = 200 mm) used for a rapid chloride penetration test (RCPT) were immersed in water for 28 days in a water-curing tank. **Results:** This study proposes a predictive model for analyzing the impact of climate change on the service life of concrete structures on Vietnam's North Central Coast. The corrosion initiation time decreases by 16.5% when the effects of both temperature rise and sea level rise are taken into consideration. When only temperature rise is taken into consideration, the rate of reduction is approximately 9.0%. These results reaffirm that climate change has a significant effect on the corrosion initiation time of concrete structures located in a marine environment.

Keywords
Climate change, temperature rise, sea level rise, reinforced concrete structures, chloride penetration.

Introduction

The study of the durability of concrete under environmental conditions plays a fundamental role in evaluating the degradation processes that occur in concrete structures over time. Most concrete degradation processes are connected to climate variables and the effects of climate change. Global studies have considered the negative impact of climate change on new and existing infrastructure (Andrade and Castillo, 2003; Saha and Eckelman, 2014; Stewart et al., 2011, 2012; Talukdar and Banthia, 2013). Increasing temperature and rising seawater levels are both climate change-related phenomena that can impact the durability of concrete structures (Medeiros-Junior, 2018; Pijaudier-Cabot et al., 2004).

Reinforcement corrosion is directly related to the durability of concrete structures. Reinforcement corrosion induced by the ingress of chlorides leads to a reduction in the durability and serviceability of the structure (Bastidas-Arteaga et al., 2010; Stewart et al., 2011, 2012). Thus, it is important to design structures that ensure durability and consider the effects of climate change. Studies have analyzed the effect of climate change on chloride penetration and the process of concrete structure degradation. Stewart et al. (2012) analyzed the impact of climate change on corrosion and damage to concrete. According to the scenarios evaluated in the study, by 2100, the probability of corrosion will increase by 6–15%. Bastidas-Arteaga et al. (2010) studied the influence of global warming on the degradation of concrete structures in a marine environment. Their findings showed that global warming can reduce the service life of structures located 3.0 km away from the coastline by 6–14 years. Medeiros-Junior et al. (2015) proposed a model to illustrate the effect of climate change on the service life of concrete structures, taking into account the effects of temperature and relative humidity on the chloride diffusion coefficients. They analyzed chloride penetration prediction models for three different scenarios. The results showed that changes in temperature and relative humidity, identified for a period of 100 years, were responsible for reducing service life by 7.8 to 10.2 years. Heede et al. (2014) showed the effect of global warming on chloride diffusivity. In untracked conditions, concrete that uses fly ash and silica fume is characterized by a very low chloride migration coefficient after 28 days (3.4×10–12 m2/s), which highly contributes to the material's estimated long service life (>100 years). Saha and Eckelman (2014) investigated the impact of corrosion on concrete structures, caused by increases in carbonation and chloride permeability. High and low emission scenarios were used for modeling carbonation and chloride-induced corrosion of concrete structures in the northeast United States.

In the sea level rise scenario, the distance between the coast and the structure decreases, while the concentration of chloride on the surface increases. Consequently, chloride penetration and corrosion increase as well (Ranasinghe et al., 2012). Gao and Wang (2017) proposed a probabilistic model for analyzing the effects of global warming and sea level rise on the service life of coastal concrete structures. Their analysis showed that climate change has a significant impact on the service life of concrete. Knott et al. (2017) presented the effects of rising groundwater, caused by sea level rise, on the service life of pavements in the coastal road infrastructure. The results indicated that service life reduction depended on the current depth to groundwater, the pavement structure, and the subgrade. This study will allow pavement engineers to effectively approach coastal road adaptation projects and significantly reduce costs. Wang et al. (2018) presented a numerical method to analyze the service life of cracked concrete, taking into account global warming and sea level rise. The effect of sea level rise on surface chloride concentration was described by applying the Bruun rule. The analysis showed that the initial service life of 50.0 years is reduced by about 6.0% when temperature rise and sea level rise are taken into account.

According to ACI 365 (Clifton, 2000; L'Hostis et al., 2011; Pijaudier-Cabot et al., 2004), service life consists of the corrosion initiation time and the corrosion propagation time. The corrosion initiation time is defined as the time it takes the chloride content at the steel rebar surface to reach critical level. The corrosion propagation time is defined as the time it takes the steel corrosion degree to exceed the critical steel corrosion (i.e., the corrosion at the concrete surface cracking point). Service life is limited to the corrosion initiation time, which equals the time it takes the aggressive substance to reach the reinforcement and induce passivation (DuraCrete, 2000). Therefore, it is necessary to predict the corrosion initiation time in order to assess the service life of structures in a marine environment. In Vietnam, some studies have also attempted to predict the corrosion initiation time of a reinforced concrete structure under the effects of the environment (carbon dioxide, chlorides, and seawater) and the combined mechanical load of environmental factors (ADB, 2013; Hanh and Furukawa, 2007; Tran et al., 2018). This study will review the influence of climate change on the penetration of chloride ions into concrete structures in a marine environment by including temperature rise and sea level rise into existing models to predict the corrosion initiation time of chloride-exposed concrete. The result will become the basis of designs for enhancing the durability of concrete structures in marine environments.

Temperature Rise and Sea Level Rise Scenario in Vietnam

The RCP8.5 (Representative Concentration Pathway) scenario, which is part of the report on climate change and level rise scenarios for Vietnam (ADB, 2013; Hanh and Furukawa, 2007; Thao et al., 2014; Thuc et al., 2016), predicts that the beginning of the 21st century will see an average annual increase in temperature between 0.8 and 1.1°C. In the mid-21st century, the temperature will likely increase by 1.8–2.3°C, with the temperature in the north likely increasing by 2.0–2.3°C and in the south by 1.8–1.9°C. At the end of the century, the temperature will likely increase by 3.3–4.0°C in the north and by

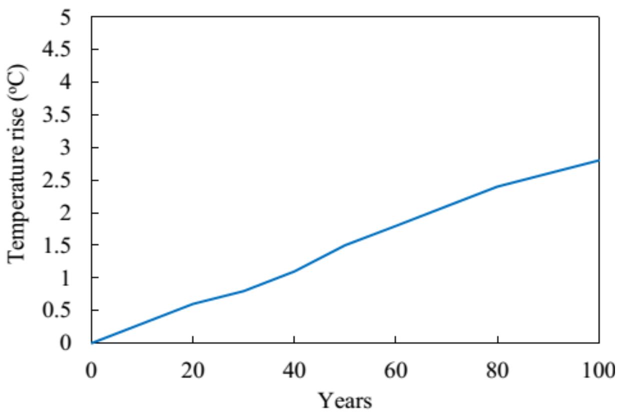

Figure 1. Temperature rise under RCP8.5

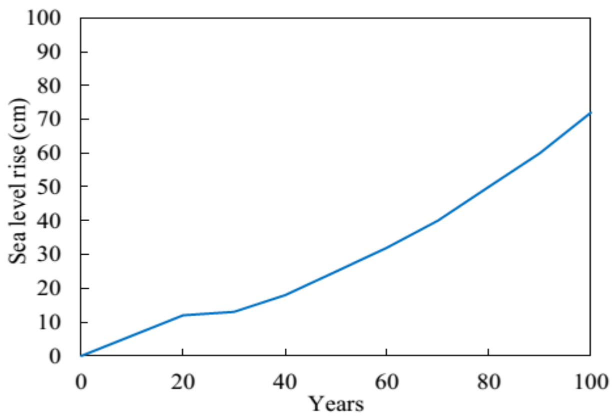

Figure 2. Sea level rise under RCP8.5

3.0–3.5°C in the south.

Under the RCP8.5 (Thuc et al., 2016) scenario, by the mid-21st century, the average sea level rise for the coastal areas of Vietnam would reach about 25 cm (from 17cm to 35 cm), and by the late 21st century, the average sea level rise for the coastal areas of Vietnam would be about 73 cm (from 49cm to 103 cm).

The North Central Coast of Vietnam is considered to be an area of extreme climatic impact, and in recent years it has been heavily affected by climate change (ADB, 2013; Hanh and Furukawa, 2007). Under the RCP8.5 scenario, the air temperature would increase by about 2.8°C due to global warming and the sea level would rise by about 72 cm over the next 100 years.

Methods

Chlorine ions intrude into the concrete parts of reinforced concrete structures in marine environments and accumulate on the reinforcement surface. When the chloride ion concentration on the reinforcement surface reaches the critical threshold, it begins to corrode the rebar. Chloride can enter concrete by many different mechanisms, such as diffusion, convection, and permeability. The chloride diffusion process occurs due to different concentration gradients. The model (Gjørv, 2011) for evaluating the service life of concrete structures was developed from the equation that calculates the the concentration of chloride on the rebar surface, based on Fick's second law, as follows:

$$C(x,t) = C_s\left(1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right), \quad (1)$$

where $C(x, t)$ is the chloride concentration at depth x of the concrete cover (% of concrete weight); C_S is the chloride concentration on the surface (% of concrete weight); D is the chloride diffusion coefficient of concrete (10–12 m^2/s); t is the considered time (years); and *erf* is the error function.

The chloride diffusion coefficient decreases over time and is determined as an exponential function of time, as follows:

$$D(t) = D_{28}\left(\frac{t_o}{t}\right)^m, \quad (2)$$

where t_o is the age of experimental concrete with chloride ion permeability; t_o = 28 days = 0.0767 years; m is the factor related to further hydration of the binder and enhanced chloride binding capacity during exposure periods; m = 0.2 (Thomas and Bentz, 2002); and D_{28} is the chloride diffusion coefficient of concrete at the age of 28 days, as determined from the experiment.

In the 21st-century climate change scenario, the environmental temperature on the North Central Coast of Vietnam will rise by about 2.8°C due to global warming (Fig. 1), and the sea level will rise by about 72 cm over the next 100 years (Fig. 2).

The Life365 Model (Service Life Prediction Model of Steel-Reinforced Concrete) proposes the dependence of the chloride diffusion coefficient on temperature, which can be described as follows:

$$D(T) = D_{28}.\exp\left(\beta\left(\frac{1}{T_0} - \frac{1}{T}\right)\right), \quad (3)$$

where β is the activity energy of chloride diffusion (β = 4300); T_0 (298°K) is the reference temperature; and T (°K) is the average temperature at the construction site.

Concrete structures can be placed under different exposure conditions in different marine zones, such as the marine splash zone, the marine spray zone, and the marine atmosphere zone. In this study, we examine concrete structures placed in the marine atmosphere zone, where the chloride surface concentration is related to the distance from the coastline to the structure, d (km). Vu and Stewart (2000) proposed that the chloride surface concentration, C_S (kg Cl-/m^3), can be determined as follows:

$C_S(d)$ = 2.95 kg Cl-/m3 concrete,
when d ≤ 0.1 km; (4)

$C_S(d)$ = 1.15 – 1.81×log10(d) kg Cl-/m3 concrete,
when 0.1 km < d ≤ 2.84 km; (5)

$C_S(d)$ = 0.03 kg Cl-/m3 concrete,
when d > 2.84 km; (6)

when sea level rise is considered, the distance from the coastline to the structure decreases, leading to increased surface chloride concentration. According to Bruun's (Pijaudier-Cabot et al., 2004) equation, when sea level rise is $S(t)$, and the average slope along the overall coastline is i_d (i_d = 0.5–1.5%), then the distance from the coastline to the structure will be reduced to:

$$\Delta d = \frac{S(t)}{i_d}. \quad (7)$$

At this time, if we account for sea level rise, the distance from the coastline to the structure will reach:

$$d' = d - \Delta d = d - \frac{S(t)}{i_d}. \quad (8)$$

The corrosion initiation time (t) is based on the time it takes the chloride concentration on the reinforcement surface to reach the corrosion threshold. As proposed by Kwon et al. (2009) and Life 365 (Bentz and Thomas, 2001; Gjørv, 2011; Thomas and Bentz, 2002), the chloride content in concrete (1.2 kg/m3 corresponding to 0.05% of concrete mass) is the reinforcement corrosion threshold (C_{cr}).

Corrosion occurs when $C(x,t) = C_{cr}$ at the time when $x = h$ (the thickness of the concrete cover), with the average surface chloride concentration (C_S).

The reinforcement corrosion initiation time due to chloride penetration can be rewritten based on Eq. (1) as follows:

$$t_i = \left[\frac{h^2}{4.D.t_o^m.\left(erf^{-1}\left(1-\frac{C_{cr}}{C_S}\right)\right)^2} \right]^{\frac{1}{1-m}}, \quad (9)$$

where erf^{-1} is the inversion of the error function.

Mixture Materials and Composition

This study used PC40 But Son cement, which has a specific gravity of 3.1 g/cm^3 and conforms with ASTM C150. We used natural sand with a maximum size of 4.75 mm as the fine aggregate, and crushed stone with a maximum size of 19 mm as the coarse aggregate. The aggregate grading was compliant with the ASTM C33 limits (ATSM, 2013). The specific gravity, bulk density (unit weight) in a compacted state, and water absorption of the coarse aggregate equaled 2.72 g/cm^3, 1.62 g/cm^3, and 0.52%, respectively. For the fine aggregate, these values were 2.68 g/cm^3, 1.71 g/cm3, and 0.9%, respectively. We investigated two normal-strength concrete types, C1 and C2, which are commonly used in construction (Table 1). Concrete C1 is usually used for substructures, while concrete C2 is mostly used for main bearing structures. The concrete mix was designed in line with ACI 211.1 (Dixon, 1991). The composition of each concrete type is shown in Table 1.

Table 1. Mixture composition for 1m^3 of concrete

Materials	Concrete C1	Concrete C2
Cement, kg	385	448
Sand, kg	811	759
Coarse aggregate, kg	1076	1076
Water, kg	170	170
Superplasticizer, l	3.46	4.03
Water/cement	0.46	0.38
Compressive strength, MPa	38.8	51.4

Results

Testing the Chloride Penetration Resistance of Concrete

The evaluation of chloride penetration was based on the ASTM C1202 test (ASTM, 2012). The cylinder specimens (d = 100 mm, h = 200 mm) used for our rapid chloride penetration test (RCPT) were immersed in water for 28 days in a water-curing tank, which was placed in a temperature room. Before the RCPT test, the cylinder was cut to a height of 50 mm. The resulting discs were sealed with two epoxy resin coats to ensure one-dimensional chloride flow through the discs. We saturated the specimens by placing them in a vacuum container and ensuring that the two end surfaces were exposed. The pressure was decreased below 1 mmHg. We maintained vacuum for four hours, before allowing air to be introduced. Then, water was introduced into the container to immerse the specimen for 18±2 hours before it was taken out and placed in the test setup.

The specimens were then placed in the testing cells. The testing process included monitoring the amount of electrical current passing through the specimen when a potential difference of 60V DC was maintained across the specimen for a period of 6 hours. In this test, chloride ions were forced to migrate out of the NaCl solution by being subjected to a negative charge; they passed through the concrete into a NaOH solution maintained at a positive potential. The results of testing the chloride permeability of two concrete types are shown in Table 2.

Berke and Hicks reported a correlation between the chloride diffusion coefficient and the chloride permeability of normal concrete (Bentz and Thomas, 2001). The following equation links the effective chloride diffusion coefficient with concrete permeability:

$$D = 0.0103\times(\text{coulombs})\ 0.84\ (10–12\ m^2/s). \quad (10)$$

Table 2 recapitulates the RCP values and the chloride diffusion coefficients (*D*) for two concrete types, C1 and C2. The chloride permeability of concrete C1 and C2 is "moderate" according to ASTM C1202.

Table 2. Chloride ion permeability and chloride diffusion coefficients for two concrete types

No.	Rapid chloride permeability, RCP (coulombs)		Chloride diffusion coefficient, 10–12 m2/s	
	Concrete C1	Concrete C2	Concrete C1	Concrete C2
1	3180	2234	9.01E-12	6.70E-12
2	3101	2290	8.82E-12	6.84E-12
3	3095	2259	8.81E-12	6.76E-12
Average	3125	2261	8.88E-12	6.77E-12

We carried out parametric studies to demonstrate the effects of temperature rise and sea level rise on the corrosion initiation time. Two types of concrete, C1 and C2, have the ratio of w/c = 0.46 and 0.38, respectively. The thickness of the concrete cover is 20–70 mm (according to Loreto, 2019) for reinforced concrete structures in marine environments). The exposure area has the marine atmosphere zone conditions. In this zone, the distance from the coastline to the structure is 300 m, the coastal slope is 1%, and the initial temperature is 25°C.

To evaluate the impact of climate change on the corrosion initiation time, caused by temperature rise and sea level rise, we ran tests for three case scenarios: no climate change (case 1), temperature rise (case 2), and both temperature rise and sea level rise (case 3). The corrosion initiation time is calculated and illustrated in Figs. 3 and 4, for all equations above and for structures using concrete C1 and C2. In cases 2 and 3, the corrosion initiation time is lower than in case 1. When considering the impact of sea level rise, the decrease in the corrosion initiation time is even more pronounced. When the w/c ratio decreases, the corrosion initiation time increases. When the thickness of the concrete cover increases, the corrosion initiation time also increases. Therefore, sea level rise has a significant impact on corrosion initiation time.

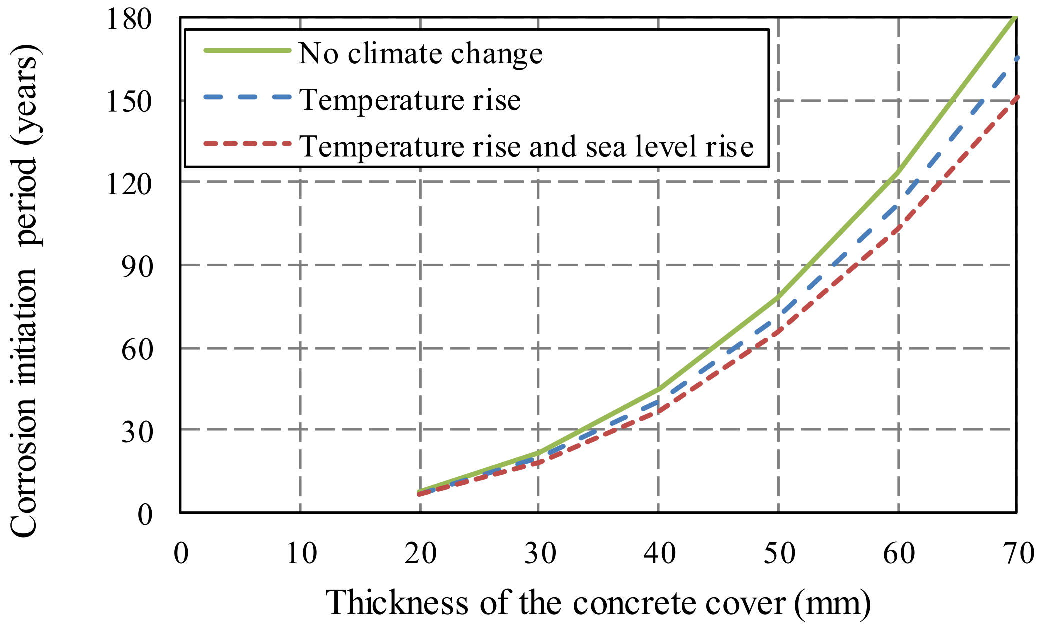

Figure 3. Corrosion initiation time for a structure with concrete C1

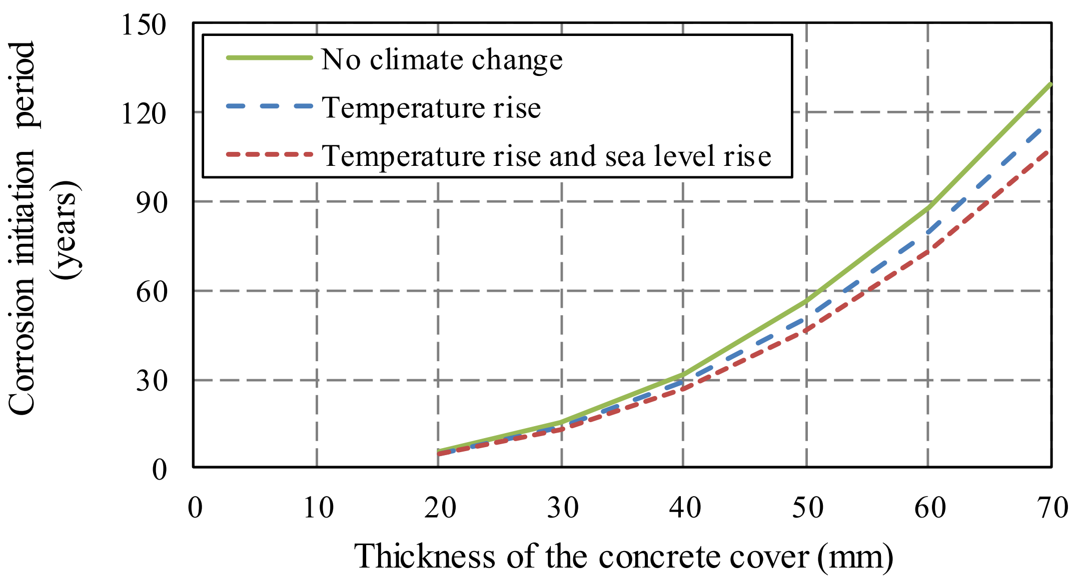

Figure 4. Corrosion initiation time for a structure with concrete C2

Table 3. Corrosion initiation time

Type	Thickness of the concrete cover (mm)	Corrosion initiation time (years)		
		No climate change	Temperature rise	Temperature rise and sea level rise
C1	30	15.5	14.1	13.0
	40	31.9	29.0	26.6
	50	55.7	50.7	46.5
C2	30	21.8	19.8	18.2
	40	44.8	40.7	37.4
	50	78.2	71.2	65.3

Table 3 shows the results of predicting the corrosion initiation time of reinforced concrete structures. According to TCVN 9346–2012 (Loreto, 2019), the standards for reinforced concrete structures in the marine atmosphere zone (where the distance from the coastline to the structure is about 0 to 1 km) are as follows. The minimum required cover thickness usually ranges from 30 to 50 mm, depending on the type of concrete, to achieve a service life of up to 50 years. When the thickness of the concrete cover is 50 mm, the corrosion initiation time of concrete C1 (w/c = 0.46) and concrete C2 (w/c = 0.38) is 55.7 years and 78.2 years, respectively, in the case of no climate change. With adjustments for temperature rise, the corrosion initiation time of concrete C1 and C2 decreases to 50.7 years and 71.2 years, respectively (the reduction ratio is about 9.0%). With adjustments for both temperature rise and sea level rise, the corrosion initiation time of concrete C1 and C2 decreases to 46.5 years and 65.3 years, respectively (the reduction ratio is about 16.5%). Thus, climate change has a major impact on the corrosion initiation time of concrete structures.

Discussion

This study provides a new approach to predicting the corrosion initiation time. This approach takes into account the effect of temperature rise and sea level rise. The study also considers the impact of global warming (temperature rise) on the diffusion coefficient. Due to a high sea level rise, the distance between the structures and the coastline decreases, and thus, the chloride concentration at the structure's surface increases. We review the effect of sea level rise on the surface chloride concentration by using Bruun's studies.

According to the climate change scenario for the North Central Coast of Vietnam, which has a tropical climate, the corrosion initiation time of reinforced concrete decreases by about 16.5% when the impact of temperature rise and sea level rise is taken into account. When only considering temperature rise, the corrosion initiation time decreases by about 9.0%. The results of this study show that climate change has a significant impact on the corrosion initiation time of reinforced concrete structures.

Acknowledgments

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