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# AN EXPERIMENTAL AND SIMULATION STUDY ON THE WET-DRY ACTION TO CRACK CAUSE OF PIER CONCRETE IN A TIDAL RIVER BRIDGE

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**Abstract.** An inspection of a tidal river concrete bridge in the Mekong River Delta discovered a large number of map cracks in most piers within the tidal range. These map cracks distribute nearly vertically and horizontally with a distance of about 15 and 20 cm. Many of them have a width over 1 mm and a depth exceeding the thickness of the reinforcement protection concrete layer.
Considering the location and the pattern of cracks, the most acceptable hypothesis on their cause was the strain gradient in concrete induced by the change of moisture content during tide rise and fall, i.e. by the effect of wet – dry action.
To verify this hypothesis, experiments on the time dependent change of concrete moisture content and volume were conducted. Based on the results of these experiments, a computer simulation was performed. The simulated crack map and pattern agreed very well with the observed ones. With the obtained results, it is reasonable to conclude that strain gradient in pier concrete induced by the wet – dry action may one of main causes of cracks in such bridge piers.

**Keywords:** concrete cracks, wet–dry action, tidal river bridge, strain gradient, computer simulation.



## 1. INTRODUCTION

A routine inspection performed in 2016 in a bridge across a tidal river in the Mekong River Delta revealed serious map cracks in most of piers. The bridge was completely constructed and opened for service in 2002. This means that cracks should occur within about 14 years after construction completion.

The bridge located about 40 km far from seaside and has eight “Super T” single spans. The piers, which have a chamfered rectangular section of 1.2 m x 5 m, were built with concrete of 30 MPa design compressive strength. The longitudinal and lateral reinforcements are of grade CIII, distributed with a distance of 150 mm and have a diameter of 28 mm and 16 mm, respectively. The thickness of concrete cover is 50 mm. In the bridge location, the average tidal range is between 1.5 and 2 meters and tidal interval is about 10 and 12 hours.

The in-depth inspection conducted two years later, in 2018, found that the crack pattern on piers are almost unchanged but the cracks get wider (**Figure 1**) and surface concrete is strongly eroded, especially at the crack’s edges. The cracks are mainly localized within the tidal zone. They distribute almost vertically and horizontally with a distance of about 15 and 20 cm at all sides of piers, but more at north-west side with sunshine in the afternoon. Some horizontal cracks have a length over several meters. Many vertical cracks stretch longer than one meter. The largest cracks measured wider than 1 mm. Using ultrasound pulse velocity (UPV) method, the depth of large cracks were measured over 10 cm, exceeded the thickness of the reinforcement cover layer. This pattern of cracks is similar from pier to pier. There are little cracks found in zones outside of the tidal range, including the constantly submerged bottom areas. The beams and abutments of the bridge remained un-cracked. The steel bar reinforcements of piers found in some boreholes are not yet corroded. The carbonation depth, measured using phenolphthalein solution, reached the values of 1.7 cm and 1.2 cm for concrete in dry zone and in tide zone, respectively.

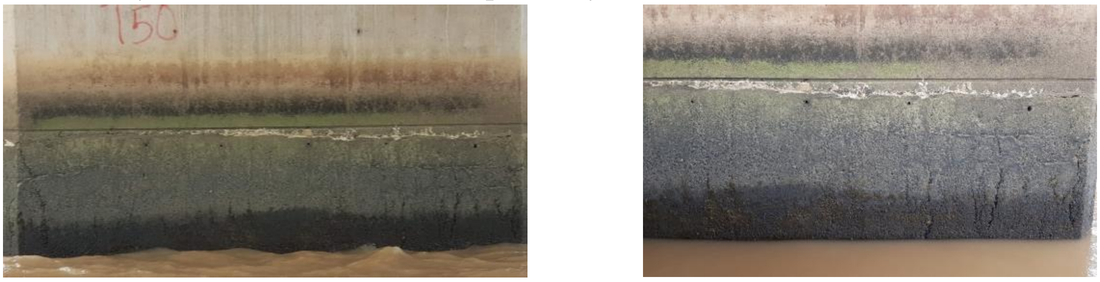



***Figure 1.*** *The change of cracks on one pier. Left: 6/2016 and right: 8/2018.*

In order to perform appropriate repair measures for these piers as well as to suggest preventive solutions, it is necessarily to find out the cause of the cracks.

As known, cracking can occur in both hardened and plastic concrete as results from any and combination of many causes. Types and causes of typical cracks are summarized in many documents like [1], [4], etc. Based on their pattern and the facts mentioned above, it can be confirmed that the being considered cracks were formed in hardened concrete and the actions like the dry shrinkage, over load, etc. could not be their causes.

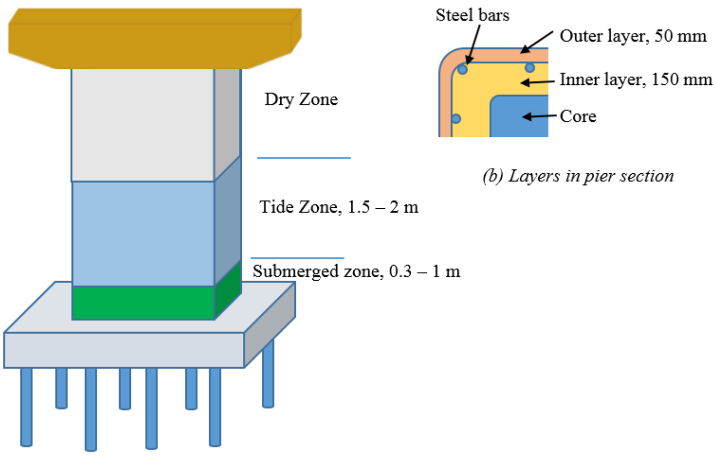
The effects of wet-dry action to the crack cause of concrete in tidal zone were mentioned in some publications. According to most of them, the wet – dry process which occurs regularly over time can rapidly increase the porosity of concrete and the accumulation of Cl- ion and $O_2$ from water and the air into it. Thereby, this action will promote the corrosion of steel reinforcement and crack in concrete [12], [8], [9]. Another effect of the wet – dry action is the activation of delayed ettringite formation [6].

Because in the being considered pier, the steel reinforcing bars were not corroded, effects of the wet-dry action should be considered in another aspect. In the report of Chen Yanjuan et al. [5], concrete under a wet-dry action in NaCl and $Na_2SO_4$ solution exhibit a severe deterioration in means of decreasing dynamic elastic modulus and increasing porosity as well as chlorine permeability. Based on these research results and the fact of surface concrete abrasion, a hypothesis to determine the cause of cracks was developed. The main idea of this hypothesis is as follow. Concrete of piers may contain some substances, which can be easily eroded in water and, under a wet-dry action caused by tide, it was deteriorated and became porous and permeable. Together with tide rise and fall, the moisture content of concrete in the surface layer changes with larger amounts and rate comparing to that in the inner layer. This produced a large strain gradient in concrete of piers. During the "dry" period, outer concrete shrinks, a large tensile stress may occur in it and cause cracking. This hypothesis was also confirmed by larger number of cracks in the north-west side with sunshine in the afternoon comparing to that in the other sides.

To verify the suggested hypothesis, experiments on the concrete properties such as mineral constituents, moisture content, volume change, etc. were performed on samples bored from many locations on a pier.

## 2. EXPERIMENTS

For convenience in this paper, two zones in piers were defined, namely "Tide Zone" and "Dry Zone". The first one is for zone in the tidal water level range and the second one is for zone over the highest water level. In each zone two layers are assigned. The "outer" is the concrete of reinforcement cover layer with a thickness of 50 mm and the "inner" is the nearby layer, which has a thickness of approx. 150 mm. The remained part of section is the "Core" (**Figure 2**).



*(a) Zones in pier*

*(b) Layers in pier section*

***Figure 2.*** *Zones and Layers in pier.*

To conduct the experiments, some core samples were drilled from different locations in a pier, some of them in "Tide Zone" and the others in "Dry Zone". In "Tide Zone", two cores were bored between the cracks and one another thru a crack. The samples were sealed in box right after bored from pier.

The experiment on ***mineral constituents*** was conducted using X-ray diffraction method. The main purpose of this experiment was to find out the mineral and chemical compositions of concrete in different locations of pier. Based on these data it should be able to determine, which components were eroded as well as whether delayed ettringite could form. But, because of the limitation of the laboratory's database, the mineral products of concrete could not be recognized properly.

The ***water absorption*** tests were performed on slices taken from along the length of bored cores, according to ASTM C642-06 [2]. Based on the results of these tests, it was possible to verify the deterioration of concrete in different locations as well as the absorption capacity of concrete. The latest value will be used to determine the change of concrete volume on moisture content. There were four series of samples represented concrete of "outer" and "inner" layers of both "Tide Zone" and "Dry Zone". All samples were first weighted to get the "natural weight" $W_n$. After drying in an oven at 105°C for 24 h, their weight was recorded as dried weight $W_d$. After stored in room temperature for one day, the samples were immersed in water for 24 h, and weighted to obtain the saturated weight $W_s$.

The saturated moisture content in percent was determined by eqn (1) and the saturated water absorption in percent was determined by eqn (2).

$$M_s = 100 \times (W_n - W_d)/W_d \tag{1}$$

$$A_s = 100 \times (W_s - W_d)/W_d \tag{2}$$

The results of these experiments are summarized in **Table 1**.

***Table 1.*** *Experimental moisture content and saturated water absorption of pier concrete.*

| Series | Moisture content – $M_s$ (%) | Water absorption – $A_s$ (%) |
|---|---|---|
| Outer, "Tide Zone" | 6.39 | 8.11 |
| Inner, "Tide Zone" | 5.26 | 6.60 |
| Outer, "Dry Zone" | 3.58 | 6.31 |
| Inner, "Dry Zone" | 5.63 | 5.60 |

This table shows the variation in the absorption capacity of concrete at different locations. Concrete in "Tide Zone" is more absorbent than concrete in "Dry Zone" and the nearer to the surface the more absorbent is concrete in each zone. The higher water absorptivity of concrete in "Tide Zone" also confirms how easy the inside concrete to get wet during the tide rise. These data showed, once again, the more deterioration of concrete exposed to tidal water comparing to one in other regions.

The experiment on ***volume change***, i.e. expansion and shrinkage, of concrete was carried out based on TCVN 6068 [11]. The change in length of samples were measured based on a reference frame with micrometer gauge (**Figure 3**). To achieve the sufficient accurate results with this measurement method, the samples should have an enough length. In addition, to obtain the difference of concrete volume change in the outer and inner layers, two sample series were created. Samples in the series "whole" contained both inner and outer layers, i.e. concrete of the whole bored samples, whilst samples in the series "inner" contained only the inner layer. The samples were first dried at 105ºC for 24 h to get the "dry length" $L_d$ and then, after stored for about 1 day at room temperature, immersed in water for 24 h to get "saturated length" $L_w$. The process is repeated 3 times for each sample.

***Figure 3.*** *Samples and equipment for measuring the change in length.*

The expansion strain of concrete was determined by eqn (3) and displayed in **Table 2**.

$$E = 100 \times \left(L_w - L_d\right) / L_d \,(\%) \tag{3}$$

***Table 2.*** *Experimental expansion of pier concrete with long samples.*

| Series | Sample | Dry length (mm) | Expansion (mm) |
|---|---|---|---|
| Whole, "Tide Zone" | M15N | 182 | 3.91 |
| Inner, "Tide Zone" | M12T | 132 | 2.48 |
| Whole, "Dry Zone" | M11N | 183 | 3.05 |
| Inner, "Dry Zone" | M13T | 133 | 2.06 |

With the assumption of constant distribution of expansion strain in each layer and from these experimental results, the elongation and then the strain values of the layers can be determined as shown in **Table 3**.

***Table 3.*** *Expansion strain of pier concrete for layers.*

| Layer | Thickness (mm), T | Expansion (mm), E | Strain (%) = E/T |
|---|---|---|---|
| Outer, "Tide Zone" | 50 (=182-132) | 1.43 (=3.91-2.48) | 0.028 |
| Inner, "Tide Zone" | 132 | 2.48 | 0.019 |
| Outer, "Dry Zone" | 50 (=183-133) | 0.99 (=3.05-2.06) | 0.020 |
| Inner, "Dry Zone" | 133 | 2.06 | 0.016 |

Since the values of expansion determined in this experiment is the change of sample's length in the saturated state compared to those in the dry state, it is possible to consider them as the reverse values of shrinkage. These results showed that with the change of moisture content, concrete in the zone exposed to tide level changing water deforms, i.e., shrinks and expanses, much more than concrete in the dry zone and that, in each zone, outside concrete deforms more than the inside one.

To simulate the ***changing of moisture content*** in concrete according to tide rising and falling, experiments on time dependent moisture content were conducted. In the water absorption experiment, core samples were sealed all sides except the surface, immersed in water and weighted for each two hours until saturated. In contrary, in the experiment on water emission (evaporation), samples were placed in an open room from saturated state and weighted for each two hours. Based on these weights and the dry weight measured in the last experiment, the time dependent moisture content of each sample was calculated and displayed in the form of table (**Table 4** and **Table 5**) and in the form of graph (**Figure 4** and **Figure 5** – for “Tide Zone”). These experimental values showed, in absorption as well as in emission, the moisture content changed rapidly in the first 4 hours and slow down after 10 hours. It’s also clear that the change rate of moisture content in the inner layer was much higher comparing to that in the outer layer. These results are very similar to data in reports of Grasley et al. in [7], Bakhshi et al. in [3], Villain et al. in [13] and Wei et al. in [14]. In profiles of the internal relative humidity change rate provided in [7] the values of 20 cm thick outer part was much larger comparing to ones of the core part.

Since the available bored samples have a limited length of about 20 cm, the change of moisture content in the core could not be determined. But, based on the obtained data and data in the mentioned publications, it was assumed that the moisture content changed in the 20 cm thick outer part and the core remained unchanged during tide fall or rise.

***Table 4.*** *Experimental time dependent moisture content during immersing.*

| Immersion time (h) | Moisture content (%) | | | |
|---|---|---|---|---|
| | “Tide Zone” | | “Dry Zone” | |
| | Outer | Inner | Outer | Inner |
| 0 | 0.85 | 0.75 | 0.96 | 0.75 |
| 2 | 3.28 | 2.88 | 2.49 | 3.17 |
| 4 | 4.78 | 3.97 | 3.48 | 4.06 |
| 6 | 5.70 | 4.72 | 4.06 | 4.74 |
| 8 | 6.42 | 5.18 | 4.51 | 5.07 |
| 10 | 6.95 | 5.52 | 4.92 | 5.20 |
| 12 | 7.27 | 5.58 | 5.15 | 5.24 |
| 14 | 7.47 | 5.64 | 5.37 | 5.27 |
| 16 | 7.60 | 5.64 | 5.47 | 5.27 |
| 24 | 7.73 | 5.70 | 5.56 | 5.30 |

***Table 5.*** *Experimental time dependent moisture content during drying.*

| Emission time (h) | Moisture content (%) | | | |
|---|---|---|---|---|
| | "Tide Zone" | | "Dry Zone" | |
| | Outer | Inner | Outer | Inner |
| 0 | 7.73 | 5.70 | 5.59 | 5.30 |
| 2 | 7.14 | 5.53 | 5.08 | 5.17 |
| 4 | 6.72 | 5.21 | 4.83 | 5.07 |
| 6 | 6.31 | 5.01 | 4.60 | 4.97 |
| 8 | 5.90 | 4.74 | 4.09 | 4.65 |
| 12 | 5.77 | 4.65 | 4.03 | 4.58 |
| 20 | 5.57 | 4.38 | 3.90 | 4.52 |
| 22 | 5.37 | 4.21 | 3.84 | 4.42 |
| 52 | 4.39 | 3.92 | 3.42 | 3.80 |

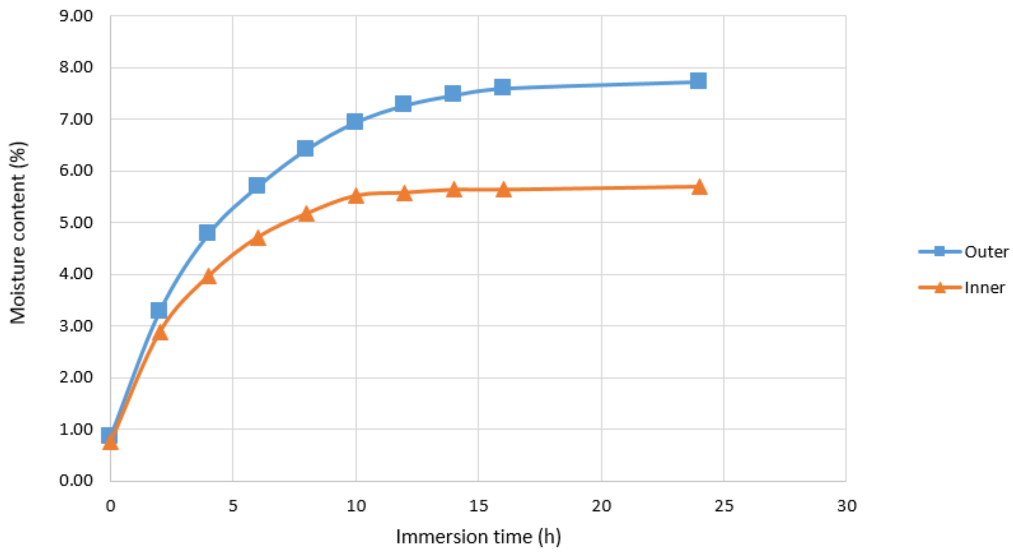



***Figure 4.*** *Time dependent moisture content during immersing of concrete in Tide Zone.*

Because the average tide interval is about 12h and concrete in "Tide Zone" exposed to a sequential immersing and drying periods of approx. 6h, the moisture content of concrete in this zone varies in certain ranges. The start values of these ranges can be taken from **Table 1**. But, in fact, the core samples were bored in the middle of the dry period, so it is reasonable to take the nearest smaller values in **Table 4** and **Table 5**. With these value ranges, 5.70% to 7.27% for outer layer and 4.72% to 5.58% for inner layer, the change of concrete moisture content in "Tide Zone" during tide rise and fall is simulated and displayed in **Figure 6**. It can be seen that, in each tide period, moisture content of both outer and inner layers varies nearly linearly during tide rise (water absorption) or tide falling (water emission) and the moisture content change of the outer layer is about two times more than that of the inner layer.

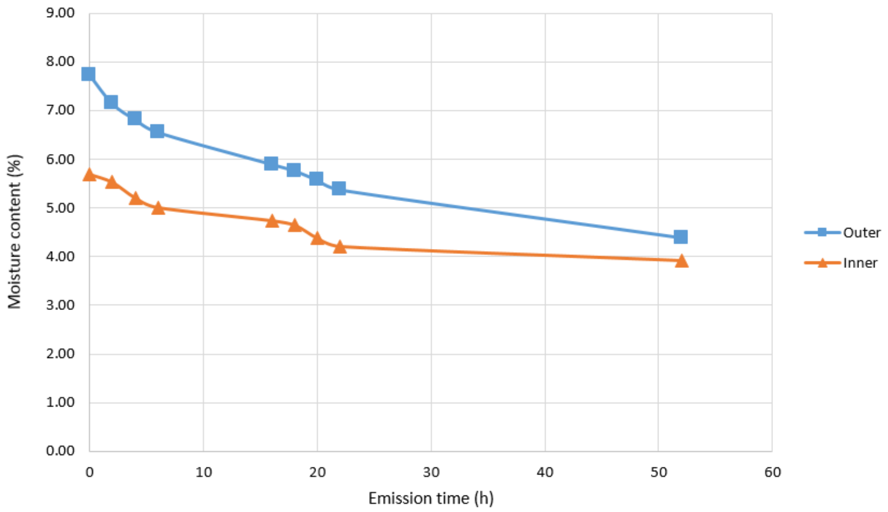



***Figure 5.*** *Time dependent moisture content during drying of concrete in Tide Zone.*

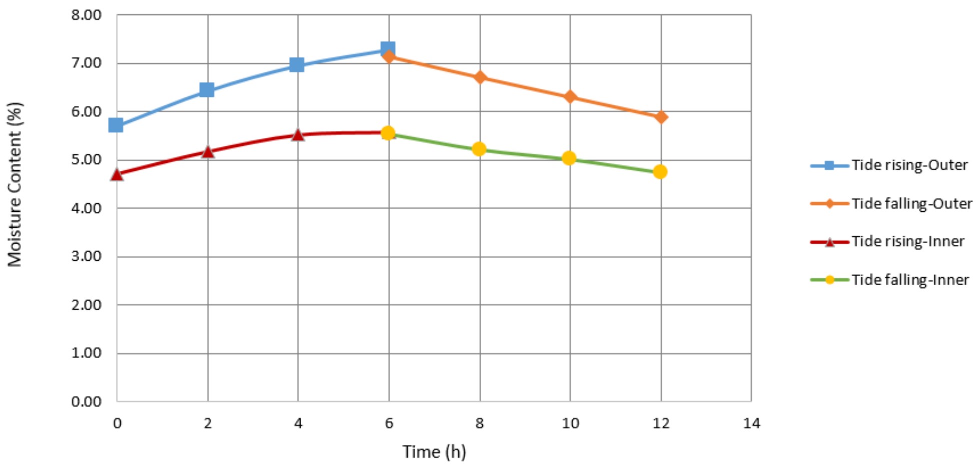



***Figure 6.*** *Change of moisture content of concrete in "Tide Zone" during tide.*

## 3. SIMULATION

The purpose of computer simulation is to verify the above suggested hypothesis on crack cause using the obtained experimental results. To conduct the simulation, it was assumed that the volume change of concrete occurs in the inner and outer layers only and the core part remains unchanged. Another assumption was the proportionality between the shrinkage or expansion strain of concrete and its moisture content. This assumption is reasonable because, after many times of shrinkage and expansion due to tide rising and falling, all irreversible deformations of concrete are eliminated.

Based on these assumptions, the strain change of outer concrete layer can be determined as follows:

- The reduction of moisture content during tide fall was

$$\Delta M = 7.27 - 5.70 = 1.57(\%)$$

- Shrinkage strain induced by this change of moisture content was

$$\varepsilon_o = \frac{E \times \Delta M}{M} = \frac{0.028 \times 1.57}{7.73} = 0.0056(\%)$$

Similarly, the shrinkage strain due to the reduction of moisture content of the inner layer was $\varepsilon_i = 0.0026\%$. So the difference of shrinkage strain of outer and inner layers was $\Delta\varepsilon_i = 0.0030\%$.

To perform the simulation, the very famous computer program for concrete analysis, ATENA ver. 3.3 [10], was used. The simulation model included the “submerged zone”, “tide zone” and about 0.6 m in the “dry zone”. With this configuration, according to the St. Venant law, the effect of actions in the tide zone could be neglected at the model boundaries. The macro elements were built according to layers as determined above because, in each macro element, only one value of strain could be set. Reinforcements were included in the analysis model. The built-in “Fracture-plastic constitutive model”, “Bilinear model” and “Bond-slip model based on CEB-FIP model code 1990” of ATENA were applied for concrete, steel and bond, respectively (**Figure 7**). “Loads” was defined as the determined shrinkage strains plus the static load taken from global analysis. As boundary conditions, the top surface is free and the bottom surface is fixed in all directions.

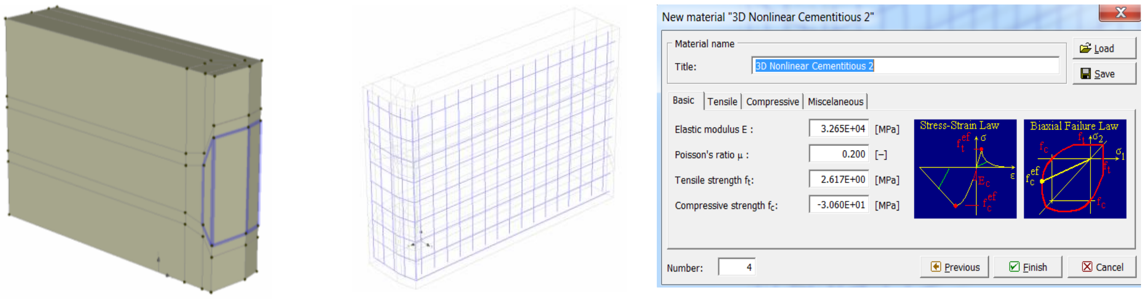



***Figure 7.*** *Left: Macro elements built according to the distribution of shrinkage strain - Model for 1/4 pier body; Middle: Reinforcement model; Right: Material parameters for concrete.*

The simulation was carried out in two “Construction cases” according to “water absorption” and “evaporation” processes. In each process, the strain of each layer was set to be changed gradually from the start to the last value in four steps according to the values in **Figure 6**.

Some results of the simulation are presented in **Figure 8** and **Figure 9**. It can be seen that, in the simulation model, cracks formed in a map quite similar to the ones observed in real piers and some cracks reached a depth of nearly 20 cm and a width of 0.1 mm. The distances between the main cracks are about 15-25 mm. The maximal stress value in reinforcement is nearly 58 MPa. The calculated depth of some cracks is somewhat bigger, while the calculated width is much smaller than the measured values, but that is reasonable. The simulation results in software display the regions in which cracks may occur but not exactly the depth and the width of cracks. Moreover, in the reality, crack depth in piers were measured at some points and it is possible, at these points, crack depths are not largest. In addition, ATENA can simulate the micro cracks in concrete, which may not be recognized by measuring equipment.

The crack opening could be explained by the long time repeated abrasion and erosion of concrete due to tide water. This general good correlation between simulation results and the observation and measurement confirmed the reasonability and feasibility of the hypothesis.

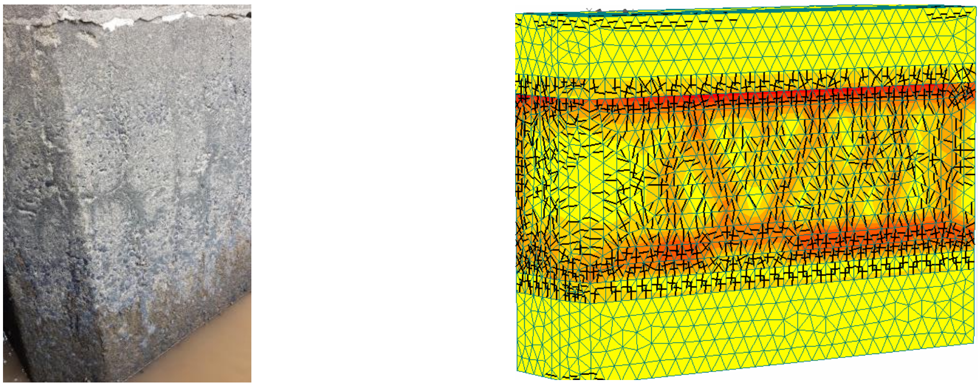


***Figure 8.*** *Comparing the simulation results and real crack pattern. Left: Cracks at pier; Right: Simulated cracks.*

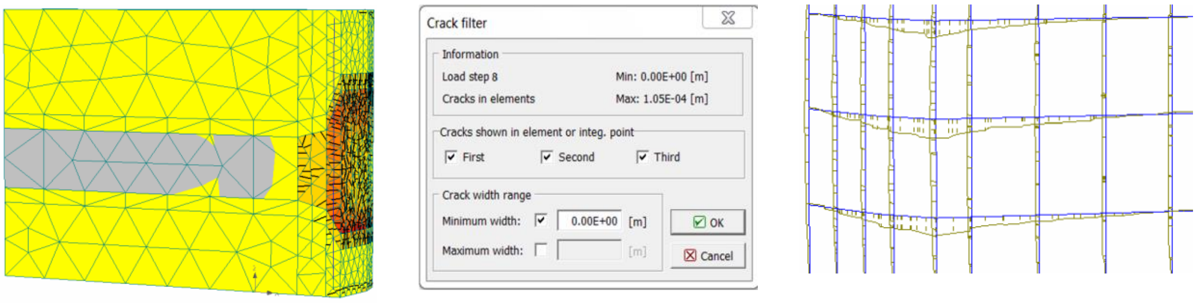



***Figure 9.*** *Left: Some simulated cracks reach a depth of about 20 cm and a width of 0.1 mm; Middle: Crack filter; Right: Stress distribution on reinforcements at pier coner.*

## 4. CONCLUSION AND OUTLOOK

There were a number of cracks found on piers of a tidal river bridge in Mekong Delta. As was known, concrete exposed to the wet–dry action caused by tide or the likes may be deteriorated rapidly. However, to find out the cause of these cracks, a hypothesis based on the deterioration state and strain gradient of concrete was suggested. A variety of experiments and computer simulation were performed to verify the hypothesis. The experimental and simulation results, which were well agreed with observation, yield to conclude that, because of the wet–dry action, concrete deteriorated and porous. The internal structure of concrete became weaker and expands or shrinks more with the change of its moisture content. With the water rising and falling according to tide, the volume of concrete in the outer layer changes much more than that in the inner layer. This large strain gradient may be the main cause of cracks on concrete of piers.

However, it should be pointed out that this is one of reasonable crack causes. Another one could be the delayed ettringite formation (DEF). Because, at the moment, the mineral products of concrete could not be determined properly by experiment, this reason could not be confirmed yet. In the near future, the concrete samples will be analyzed again to obtain their mineral and chemical constituents. Based on these data, further analysis and conclusion can be made. Moreover, only with these data it could be possible to suggest proper preventive solutions for bridge piers on such tidal river.

**REFERENCES**

[1] ACI, Causes, Evaluation and Repair of Cracks in Concrete Structures, ACI 224.1R-07, 2007.

[2] ASTM International, Standard Test Method for Density, Absorption, and Voids in Hardened Concrete - C 642 – 06, 2006.

[3] M. Bakhshi, B. Mobasher, C. Soranakom, Moisture loss characteristics of cement-based materials under early-age drying and shrinkage conditions, Construction and Building Materials, 30 (2012) 413-425. https://doi.org/10.1016/j.conbuildmat.2011.11.015

[4] Bluey Technologies Pty Ltd, Evaluating Cracking in Concrete, Australia & Asia-Pacific.

[5] Chen Gao, Tang Shen, Performance of concrete subjected to severe multiple actions of composite salts solution under wet-dry cycles and flexural loading in lab, Journal of Wuhan University of Technology-Mater. Sci. Ed., 32 (2017) 830–837. https://doi.org/10.1007/s11595-017-1676-9

[6] B. Godart, L. Divet, Lessons learned from structures damaged by delayed ettringite formation and the French prevention strategy, Fifth international conference on Forensic Engineering, Institution of Civil Engineers, France, 2013.

[7] Z. C, Grasley, D.A. Lange, Modeling Drying Shrinkage Stress Gradients in Concrete, Journal of Testing and Evaluation, 26 (2002) 115-122.

[8] P. K. Mehta, Concrete in the marine environment, Taylor & Francis e-Library, 2003.

[9] K. Sakai, Integrated Design and Environmental Issues in Concrete Technology, Taylor & Francis, 1996.

[10] Cervenka Jendele, Cervenka, ATENA Program Documentation, Prague, August 23, 2007.

[11] TCVN 6068:2004, Tiêu chuẩn quốc gia TCVN 6068:2004 về Xi măng poóc lăng bền sunphat - Phương pháp xác định độ nở sunphat, 2004. (in Vietnamese)

[12] Dinh Anh Tuan, Nguyen Manh Truong, Vietnam Academy for Water Resources (VAWR), Thực trạng ăn mòn, và phá hủy các công trình bê tông cốt thép bảo vệ bờ biển nước ta (State of corrosion and destruction of coastal reinforced concrete works in our country).

[13] G. Villain et al., Characterization of Water Gradients in Concrete by Complementary NDT Methods, International Symposium Non-Destructive Testing in Civil Engineering, Berlin, Germany 2015.

[14] Y. Wei, X. Gao, W. Hansen, Influential Depth by Water Absorption and Surface Drying in Concrete Slabs, Transportation Research Record: Journal of the Transportation Research Board, 2342 (2013) 76–82. https://doi.org/10.3141/2342-09