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Corrosion Monitoring System in Reinforced Concrete using GPRS

Jhon Andres Gomez Portilla[1], José Luis Ramírez Arias[2], Astrid Rubiano Fonseca[3]
[1]Universidad Militar Nueva Granada, jhon.gomez@unimilitar.edu.co, Republic of Colombia.
[2]Universidad Militar Nueva Granada, jose.ramirez@unimilitar.edu.co, Republic of Colombia.
[3]Universidad Militar Nueva Granada, astrid.rubiano@unimilitar.edu.co, Republic of Colombia.
*Corresponding author, Professor, E-mail: jhon.gomez@unimilitar.edu.co

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Abstract
Corrosion is a factor that degrades bridges and structures; for this reason, it is important to study it to minimize its impact. Corrosion is generally presented by carbonation and concentration of chloride ions. In this work was designed and implemented a system that allowed the measurement of the electrical resistivity of concrete, the concentration of CO2, relative humidity, and concrete temperature; through this is possible to know the structure's corrosive states.

Keywords: Reinforced Concrete, Carbonation, Chloride ions, Corrosion, GPRS

1. Introduction

Reinforced concrete is one of the most used materials for the construction of civil structures, thanks to its mechanical properties and easy handling. However, reinforced concrete has a disadvantage, which is very susceptible to corrosion. The concrete reinforcements are made of Iron, which comes in different presentations. (Aperador, Delgado, & Vera, 2011; Liang, Qu, & Liang, 2002).Iron rods are the most used. It is known that the most influential factors in the development of corrosion in concrete structures are the carbon dioxide CO2 present in the atmosphere and the chloride ions CL, primarily present in areas near marine waters. When the reinforcing steel is affected by these factors, a gradual degeneration of the structures is created, called corrosion. (Poursaee, 2009)

Other equipment containing different electrochemical techniques can be used to evaluate the degree of deterioration of embedded reinforcement steel in particular; the advantages of these techniques over the EIS technique are the speed of measurement, use of small disturbances in the interface and sensitivity, in addition to being non-destructive tests, the most used are: measurement of half-cell potential (*Ecorr*), polarization resistance *(Rp*) and cyclic voltammetry, each of them can provide information about the conditions of the steel-concrete interface and with it the degree of deterioration that is present in the armature, some solutions are also proposed to stop this deterioration. (Broomfield, Davies, & Hladky, 2002)

S. Feliu (2005) exposes the problems faced when trying to measure in situ the speed of corrosion of steel in reinforced concrete in large structures; the article deals with some problems related to the determination of the true value of polarization resistance, the time associated with the corrosion process, and the use of a guard ring to limit the electrical signal to a defined area of reinforcement. The results corroborate the need for time as a constant value independent of the area affected by the electrical signal. However, with some exceptions, as for the guard ring, they show the importance of reaching a critical ratio between the currents flowing from the guard ring and the counter electrode.(Feliu, González, Miranda, & Feliu, 2005)

O. Poupard (2006) investigated how chloride induced the corrosion of steel embedded in reinforced concrete, which was exposed in the marine environment for 40 years; for his evaluation, the author made visual observations, electrochemical evaluation, carbonation depth measurement, and chlorine content, half-cell potential measurements were used to locate the areas of corrosion, he obtained that the interpretation based on the gradient of the potential was in agreement with the true state of damage of the concrete; some complementary destructive and non-destructive methods were applied to observe the true corrosion state of the steel bars and to characterize the corrosion products at the steel-concrete interface. He concluded that physicochemical measurements confirmed that chlorine ions are solely responsible for the presence of corrosion.(Poupard, L'Hostis, Catinaud, & Petre-Lazar, 2006)

Zin-Taek Park (2005) designed a system to monitor the corrosion velocity of the steel bar embedded in concrete at the laboratory level; measurements of the half-cell potential, linear polarization resistance (LPR), and electrochemical impedance spectroscopy (EIS) were used to evaluate the corrosion behavior of the steel bar integrated into the concrete. In this study, the results of the corrosion behavior of the steel showed a coherence between the data obtained by monitoring the potential of half a cell, LPR, and EIS measurements. In addition, a steel-copper sensor was used as an auxiliary electrode which showed a good correlation in the concrete environment between the output of this sensor and the corrosion velocity of the steel bar. (Park, Choi, Kim, & Chung, 2005)

T.A. Soylev (2003) studied the effect of the quality of the reinforcing steel in terms of its response to corrosion so that I relate the defects with the holes caused by bleeding and segregation of fresh concrete under the horizontal reinforcing bars, these defects increase with the depth of the concrete under the horizontal reinforcement and depend on the bleeding capacity of the concrete mixture. The polarization resistance technique on the corroded surface measured corrosion. The results led to the conclusion that steel corrosion in concrete increases along the section height of the rod. In addition, for other steels of lower quality, the porosity measure is high, which is linked to a high corrosion speed, what was concluded from this study is that the corrosion in the steel will exist, but also this deterioration of the material is dependent on the quality of the steel. (Söylev & Richardson, 2008)

D.W. Law (2004) experimented to find the weight loss values of steel bars embedded in Portland Cement concrete; the weight loss measurements were first calculated and then monitored using the LPR technique, three bars were placed attached and each in a different medium generating three types of corrosion, chloride-induced corrosion, carbonation induced corrosion, and minimum corrosion causing nitrogen; weight loss for each bar due to corrosion was recorded, instantaneous LPR measurements were also taken for each bar at regular intervals throughout the exposure period. (Law, Cairns, Millard, & Bungey, 2004)

Beena (2017) developed a non-destructive technique using ultrasound waves to monitor the corrosive state of CFST structures. These have been used to monitor defects in concrete-filled steel tubes, simulating pitting. Pulse transmission was used to monitor good specimens and simulate damaged specimens. This methodology allows monitoring steels immersed in concrete under accelerated corrosion by chloride ions. (Beena, Shruti, Sandeep, & Naveen, 2017)

Xingji Zhu (2018) researched a mathematical model based on polynomial functions to determine the effect of carbonation on changing the diffusion coefficient of chloride ions. In this model assuming linear diffusion, results were obtained for the depth of carbonation and the concentration of chloride ions as a function of exposure time and mix proportions in concretes. (Zhu, Dai, Tan, Meng, & Xu, 2018)

Hietpas (2005), Implemented a sensor embedded in reinforced concrete structures for early detection and prevention of corrosion. The device evaluates the condition of the steel using ultrasound techniques and then uses a wireless data transmission system; this system transmits the data wirelessly based on an antenna that operates in a bandwidth of 2.4 to 2.5 GHz. (Hietpas, K., Ervin, B., Banasiak, J., Pointer, D., Kuchma, D. A., Reis, H., & Bernhard, 2005).

Yang (2019), Proposed a theoretical model to predict the service time of concrete subjected to chloride corrosion and fatigue loading. For the development of this model, the author divided the concrete into two parts, microcracks and matrix. Considering the variation in the area of microcracks caused by fatigue, an equation of the chloride diffusion coefficient was established, and a predictive model based on Fick's second law was subsequently developed. The model is suitable for predicting the service life of concrete subjected to chloride ion attacks. (Yang, Guan, Liu, Li, & Pan, 2019).

Kim Sehwan (2013), Invented a system to feed corrosion monitoring systems based on the difference in galvanic corrosion potential between a metallic infrastructure and a reference electrode. In addition, they used supercapacitors adopted as ESE to compensate for battery limitations. The most important results of this research show that the storage schemes significantly reduce the overloading of the charging circuits, allowing a capacitor up to 350F to be charged under minimal corrosion power. (Kim Sehwan & Na Ungjin, 2013).

It is important to continuously monitor the structure's condition to verify the corrosion's progress. Concrete structures corrode over time. Mainly because they are exposed to environmental conditions; for this reason, monitoring systems are implemented to make a continuous follow-up of the structures and to study and propose maintenance strategies to reduce the impact or risk of possible breakdowns. The present paper evaluates the behavior of structural steels in concrete using different techniques. For it, equipment was developed that allowed the study of the corrosion process with the possibility of being used in the field.

2. Experimental

The proposed corrosion monitoring system comprises three major subsystems: the electronic system, the software system, and the mechanical system; most of the equipment is composed of electronics and software development or interface but has a mechanical part. The methodology carried out for the development of the system is shown in Fig 1.

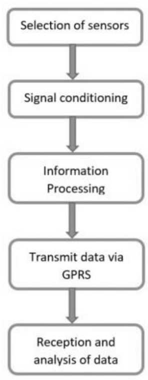


Fig. 1 Design Methodology

2.1 Selection of sensors

The basis of this document is to transmit using an embedded system: the electrical resistivity of the concrete, carbon dioxide, relative humidity, concrete temperature, and ambient temperature since these variables make it possible to analyze the degradation of the steels inserted in concrete and how they affect their durability. To measure these variables, sensors, and techniques were implemented to measure the corrosive state, Fig 1.

2.1.1 Electrical resistivity sensor
The 4 - point technique (Wenner Method) is used to measure the electrical resistivity of the concrete, which is the most effective technique. The electrodes used were stainless steel rods 20cm length, a Portland probe (type 1) 30cm length, and 15cm in diameter; the rods are spaced 2.5cm and are at a depth of 14cm, fig 2.


Fig. 2 Concrete electrical resistivity sensor

Under the directives of the ASTM standard ASTM G57-06, a square signal is generated at 97 Hz to apply current to the external electrodes. The electrical resistance of the concrete was calculated using ohm's law, considering the voltage measured at the internal electrodes and the value of the current applied. With the value of the electrical resistance of the concrete R and the geometric parameters of the depth of the electrodes b and its separation a. Apply Eq.(1) and obtain the resistivity values ρ at Ohm*cm.

$$\rho = \frac{4\pi Ra}{\left(1 + \frac{2a}{\sqrt{a^2 + 4ab^2}} - \frac{2a}{\sqrt{4a^2 + 4ab^2}}\right)} \tag{1}$$

For the measurement of the temperature inside the concrete industrial, PT-100 was used; this sensor is deterioration resistant, and for these reasons, it was chosen to measure the temperature inside the concrete. Fig 3 illustrates the mounting of the PT-100 sensor.


Fig. 3 Temperature sensor

2.1.2 Environmental condition sensor.
Environmental conditions directly influence the development of corrosion in reinforced concrete structures, either by carbonation or by chlorides. Although there are many environmental factors, the most known and influential in corrosion are the relative humidity of the medium, carbon dioxide,

and ambient temperature (Fig 4). According to the design characteristics of the prototype, the sensor selected to perform these measurements is a robust sensor of industrial type; this has the advantage of requiring little maintenance, allowing the autonomy of the monitoring system, and ensuring the sending of data to a central server in real-time.

Fig. 4 Sensor COMET H6320

2.2 Signal conditioning

Conditioning circuits were used for each of the sensors to adapt the signals to be processed by the main controller, which uses an ADC digital analogy conversion system. The following sections will talk about the microcontroller used.

2.2.1 Temperature sensor conditioner

The Siemens TH-200 was used to condition the temperature sensor signal. The output delivered by the conditioner is a current of 4 to 20 mA; for signal processing, a resistance was coupled to obtain a constant voltage easily acquired by the ADC (analog-digital converter), also implemented a buffer circuit which is composed of an operational amplifier; this allows an impedance coupling between the microcontroller and the TH-200 conditioner, Fig 6.

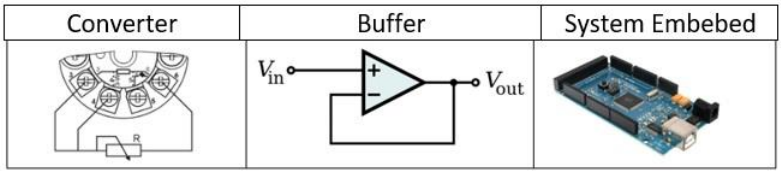


Fig. 6 Conditioning sensor PT-100

2.2.2 Electrical resistivity sensor conditioner

The conditioning of the electrical resistivity sensor is made up of two parts, the first part conditions the current signal that is applied to the external electrodes of the sensor at the stipulated frequency; the second part condition the voltage signal that is obtained between the internal electrodes of the sensor, Fig 7.

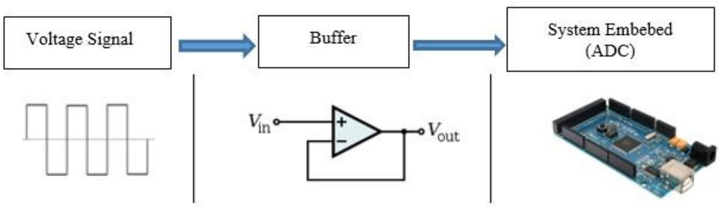


Fig. 7 Conditioning Resistivity Measurement System - Voltage Signal

The electrical resistivity of the concrete is calculated using Eq (1).

2.2.3 Environmental Sensor Conditioner

The environmental sensor manages the MODBUS RTU communication protocol and RS232 serial interface. It is based on master-slave architecture. To get the data of the three variables, the sensor was used as slave and a microcontroller as the master. Fig 8.

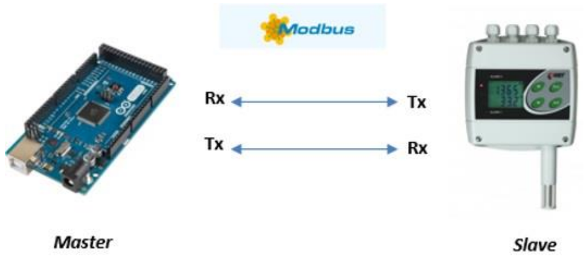
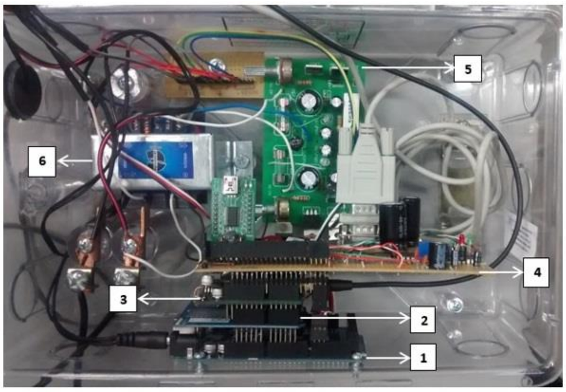


Fig. 8 MODBUS communication with Sensor H6320

2.3 Processing

GSM reception and GPRS transmission system: As shown in Fig 9 (Data Processing and Acquisition), the SD Shield was used to store the data on a memory card; this data is stored in a .txt file. Once the data had been acquired and processed, the GPRS module sent the .txt file to a web server which houses a supervisor and a *php* database to manage the data.

The system comprises several parts, which are integrated into each other, resulting in the final corrosion monitoring system. Fig 9 illustrates the main system with each of its component parts.



1. System Embebed 4.Instrumentation Plate
2. Shield SD 5.Voltage Source
3. GPRS module 6.Transformer

Fig. 9 Assembly of the integrated monitoring system

The housing that protects the system is made of hermetically sealed plastic to protect it from the humidity of the medium. The atmospheric measurement sensor's electronics are located inside this box to protect it, and the part that senses the variables is exposed to the medium. Fig 10 shows the integrated monitoring system with the COMET H6320 sensor and the coupled temperature and resistivity sensors.

Fig. 10 Integrated monitoring system.

3. Results and discussion

Several cylindrical samples were fabricated using type I Portland concrete, with a diameter of 5 centimeters and a height of 10 centimeters reinforced with structural steel.

3.1 Carbonation test and environmental monitoring

The concrete specimen was subjected through a climatic chamber to an environment with a CO2 concentration of 2000 ppm at a temperature of 20C and a relative humidity of 45.7 % (data that were released by the environmental monitoring system developed) during 240 hours, time in which the gas penetrated the concrete specimen through the exposed faces.

After finishing the test, the specimen was extracted from the aggressive medium. It was dissected using a transversal cut to use it to determine the carbonation profile, which was revealed through the use of a 1 % phenolphthalein solution. 25 length measurements were taken around the colorless region, obtaining an average carbonation depth of 13.8 mm.

3.2 Test of electrical resistivity of concrete and internal temperature

To determine the system's functionality for monitoring electrical resistivity and internal temperature of the concrete, specimens of 3 centimeters in diameter and 25 centimeters in length were manufactured, equipped with a *Wenner Array* and an RTD PT100. The values produced by the system were monitored for 24 days, during which time an average electrical resistance of 245 kΩcm was obtained, as shown in Fig 11.

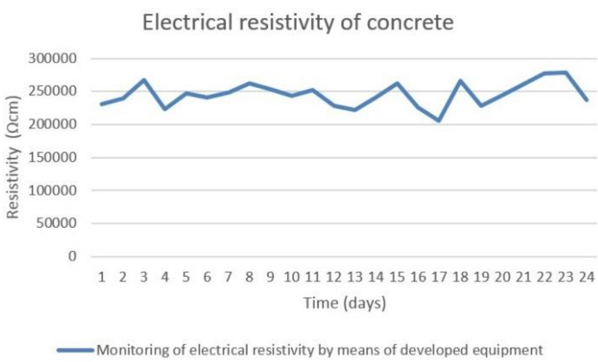


Fig. 11 Electrical Resistivity of Concrete

The average value found for the electrical resistivity corresponds, according to Fig 11, to a null corrosion risk (table 1). Similarly, the internal temperature of the specimen was monitored, where the average temperature was 18.65 °C, a temperature that was contrasted with the Fluke infrared thermometer.

Resistivity(Ohm.cm)	*Corrosion risk*
Greater than 20000	Null
10000 to 20000	Low
5000 to 10000	High
Less than 5000	Very High

Table. 1 Corrosion risk according to resistivity values (Song & Saraswathy, 2007)

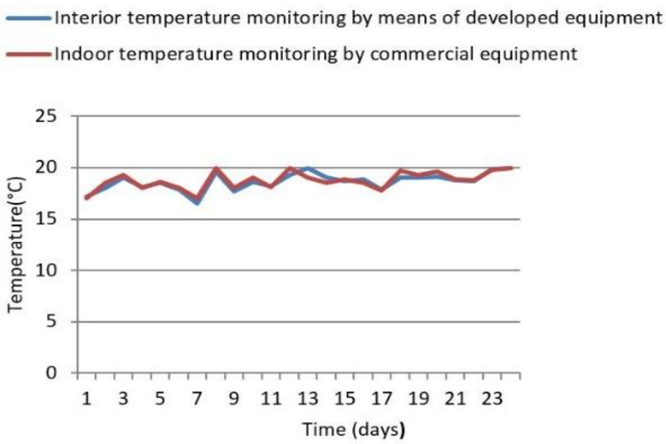


Fig. 12 Concrete internal temperature monitoring

According to Fig 12, the temperature did not increase significantly to influence the corrosion advance directly, nor was sufficiently low temperatures experienced. A considerable increase in temperature is needed to increase the carbonation rate and, thus, corrosion.

3.3 Receipt and analysis of data

During the tests, all the data were stored in the physical micro-SD memory from the previous stage; the web server was updated to receive much larger information packages via FTP protocol. As a result, the .txt files generated weigh an average of 20 Kbytes, offering a long duration of autonomy before performing any maintenance.

4. Conclusions

The study developed a corrosion monitoring system capable of determining the ambient temperature, the relative humidity of the medium, and the concentration of carbon dioxide; variables influence the advancement of carbonation and the entry of chloride ions into reinforced concrete structures.

The developed system allows us to determine the corrosive state and the cause of this with an average error of 6.28 % for the probability of corrosion concerning commercial equipment used as standard.

The developed system can be manipulated from any part according to the mobile communication system (GSM/GPRS) designed by Guillermo et al.; in this way, the specialists and personnel can have the information in real-time using any equipment with an Internet connection.

The equipment designed allows us to know in a remote way (in-situ) the state of the corrosion in the structures of reinforced concrete, taking as base the use of atmospheric sensors and the technique of electrical resistivity of the concrete (*Wenner Array*); In this way, the sending of personnel and equipment to the area is avoided giving; as a result reduction of costs.

Subjecting the specimen to the aggressive, controlled environment (Carbonation) is observed as the CO2 to a concentration of 2000 ppm degenerates the reinforcement in 240 hours; The concentration of CO2 varies according to the pollution of the medium, and this way will depend on the rate of carbonation, the equipment developed allows for tracking this variable and thus knowing the progress of corrosion in reinforced concrete structures.

References

1. Aperador, W., Delgado, A., & Vera, E. (2011). Monitoreo mediante EIS del acero embebido en un concreto de escoria activada alcalinamente expuesto a carbonatación. *Revista Ingeniería de Construcción*, *26*(1), 81–94. https://doi.org/10.4067/s0718-50732011000100005
2. Broomfield, J. P., Davies, K., & Hladky, K. (2002). The use of permanent corrosion monitoring in new and existing reinforced concrete structures. *Cement and Concrete Composites*, *24*(1), 27–34. https://doi.org/10.1016/S0958-9465(01)00024-5
3. Feliu, S., González, J. A., Miranda, J. M., & Feliu, V. (2005). Possibilities and problems of in situ techniques for measuring steel corrosion rates in large reinforced concrete structures. *Corrosion Science*, *47*(1), 217–238. https://doi.org/10.1016/j.corsci.2004.04.011
4. Guillermo, R.-R., William, A.-C., & Emilio, D.-T. (2015). Diseño de sistema de monitoreo remoto para evaluación de la corrosión en estructuras de concreto reforzado sometidas a ion cloruro. *Ingeniería, Investigación y Tecnología*, *16*(4), 565–572. https://doi.org/10.1016/j.riit.2015.09.008
5. Law, D. W., Cairns, J., Millard, S. G., & Bungey, J. H. (2004). Measurement of loss of steel from reinforcing bars in concrete using linear polarisation resistance measurements. *NDT & E International*, *37*(5), 381–388. https://doi.org/10.1016/J.NDTEINT.2003.11.003
6. Liang, M. Te, Qu, W., & Liang, C. H. (2002). Mathematical modeling and prediction method of concrete carbonation and its applications. *Journal of Marine Science and Technology*, *10*(2), 128–135.
7. Park, Z. T., Choi, Y. S., Kim, J. G., & Chung, L. (2005). Development of a galvanic sensor system for detecting the corrosion damage of the steel embedded in concrete structure: Part 2. Laboratory electrochemical testing of sensors in concrete. *Cement and Concrete Research*, *35*(9), 1814–1819. https://doi.org/10.1016/j.cemconres.2003.11.027
8. Poupard, O., L'Hostis, V., Catinaud, S., & Petre-Lazar, I. (2006). Corrosion damage diagnosis of a reinforced concrete beam after 40 years natural exposure in marine environment. *Cement and Concrete Research*, *36*(3), 504–520. https://doi.org/10.1016/j.cemconres.2005.11.004
9. Poursaee, A. (2009). Automatic system for monitoring corrosion of steel in concrete. *Advances in Engineering Software*, *40*(11), 1179–1182. https://doi.org/10.1016/j.advengsoft.2009.05.001
10. Song, H. W., & Saraswathy, V. (2007). Corrosion monitoring of reinforced concrete structures - A review. *International Journal of Electrochemical Science*, *2*(1), 1–28.
11. Söylev, T. A., & Richardson, M. G. (2008). Corrosion inhibitors for steel in concrete: State-of-the-art report. *Construction and Building Materials*, *22*(4), 609–622. https://doi.org/10.1016/j.conbuildmat.2006.10.013
12. Beena, K., Shruti, S., Sandeep, S., & Naveen, K. (2017). Monitoring degradation in concrete filled steel tubular sections using guided waves. Smart Structures and Systems, 19. https://doi.org/10.12989/SSS.2017.19.4.371

13. Hietpas, K., Ervin, B., Banasiak, J., Pointer, D., Kuchma, D. A., Reis, H., & Bernhard, J. T. (2005). (2005). Ultrasonics and electromagnetics for a wireless corrosion sensing system embedded in structural concrete. Smart Structures and Systems, 1(3), 267–282. https://doi.org/https://doi.org/10.12989/SSS.2005.1.3.267
14. Kim Sehwan, & Na Ungjin. (2013). Energy harvesting techniques for remote corrosion monitoring systems. Smart Structures and Systems, 11(5), 555–567. https://doi.org/https://doi.org/10.12989/SSS.2013.11.5.555
15. Yang, T., Guan, B., Liu, G., Li, J., & Pan, Y. (2019). Service life prediction of chloride-corrosive concrete under fatigue load. Advances in Concrete Construction, 1, 55–64. https://doi.org/https://doi.org/10.12989/acc.2019.8.1.055
16. Zhu, X., Dai, X., Tan, Y., Meng, Z., & Xu, L. (2018). Ingress of chloride ions with carbonation: parameter estimation and analytical simplification. European Journal of Environmental and Civil Engineering, 0(0), 1–22. https://doi.org/10.1080/19648189.2018.1528894