Seismic performance of bridge piers

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Abstract. The bridges that constructed in earthquake-prone areas perhaps subjected to sudden earthquake through their construction and service period. So, attentions should be pushed during bridge design specially, as they are one of the main civil infrastructures. The bridge piers are the main parts of bridges whether they are built across river or even as an express highway projects. This paper presented an experimental study of seismic performance of concrete bridge piers. Several important parameters have been studied such as acceleration response, seismic displacements, the bridge pier model settlement and the failure mechanism. Principles of physical modeling are used to fabricate two bridge pier models and shaking table (1-g tests) were performed under 0.82g waveform (i) Chamfered bridge pier built on saturated cohesionless soil (test-1) (ii) Oblong bridge pier built on saturated cohesionless soil(test-2). The output results included the acceleration response in term of the time acceleration and acceleration response spectra, failure mechanism during shacking, seismic displacement of the bridge pier model. The results show that the amplification in the acceleration is increases significantly at the top of the bridge pier. The seismic displacement is suddenly increased sharply due to strong motion. Overturning failure mechanism about the heel of the bridge pier has been observed in test-1 and test-2.

Keywords: Acceleration, Bridge pier, Earthquake, Earth pressure, Seismic performance.

1. Introduction

Very risk effects on infrastructures, highways and bridges are noticed around the world due to earthquakes. As the earthquakes quickly impacted on infrastructures, leading to sudden building breakdown, destruction of highways, bridges collapse, fires and severe floods, thus tens of dollars have been spend by government post-earthquakes during the rehabilitations of the infrastructures. Many destructive earthquakes in last years occurred which were reasons of thousands of death tolls with millions homeless and injured. Socio-economic development is strongly influenced by such disaster due to spread of diseases as well as the psychological effects in societies for many years. Many researches are conducted to investigate how the earthquakes effect on the structural elements of infrastructures, the long rise building and the structural bridges parts (i.e. girder, decks, piles and piers) and this is not surprising why authors used different small scale model to improve the knowledge and understanding the earthquakes scientific comprehension and the structural dynamic responses. The bridges that constructed in earthquake-prone areas perhaps subjected to earth shake through their construction and service period. So, attentions should be paid to bridge piers in particular, as they are the main parts of the bridge’s structural elements. The structure response for the earthquake effect relies on the loading characteristics with the material behavior of the structural component itself. The concrete material action under the reinforced concrete structure is so complex and it has been investigated with many research studies and executed for the models to simulate it.
Several shaking table tests were conducted for evaluation the performance of bridge structures. Johnson et. al., 2008 [1] at the University of Nevada studied soil-foundation-structure interaction where the bridge was exposed to low intensity and high intensity earthquake excitation. Chen et al. 2018 [2] investigated the shaking table tests on two 1/7 scale, tall-pier models on the long mode effects to show the importance of long model effect on the seismic performance of concrete bridges piers also they found that correlation were weak between curvature at the pier base and displacement at the pier top, so that the results refer that displacement not reliable damage to tall pier also the results found that contribution long model may lead formation region of plastic on the mid height of piers. Tubaldi et. al., 2014 [3] through analytical method, the authors studies the effect of higher order models on the dynamic response and seismic performance of slender bridge piers and could overcome some of limitation on the models that used in the last studies, also the study show some of important evident for dynamic behavior of bridge piers that required a lot of investigation. Chen et. al., 2016 [2] discussed both of initial yielding and ultimate state through dynamic analysis for tall piers model by using fiber beam elements. The results showed that seismic response of tall piers with design displacement lead to higher errors. Loli et al. 2014 [4] conducted a pilot study through a series of dynamic centrifugal experiments on 1:50 bridge piers models with a realistic representation of soil behavior in order to demonstrate the concept of unconventional design that makes concrete bridge piers safe under intense seismic excitement. Neaz et. al., 2012 [5] identified the local damage parameter for the bridge piers. Such damage parameters however may indicate the bridge seismic damage states as supported only via piers. As described by Wang et. al., 2005 [6], the bridge pier is replaced in the seismic bridge structure design with the elastic system possessed effective damp for the analyzing its nonlinear seismic response. It is termed as "substitute structure technique" and proposed seismic design displacement technique for the RC bridge pier. Dong 2006 [7] checked the pier shear strength with the utilization of the capacity design concept for avoiding the brittle shear failure. Palermo et. al., 2005 [8] researched the execution of the "cross breed" controlled shaking framework connected to connect docks and the worldwide reaction of this framework with customary and sporadic wharf designs. Results demonstrate improved execution of shaking frameworks when contrasted with regular malleable enumerating. This examination will additionally explore the seismic reaction of shaking span docks. There are various reasons for bridge pier failures which include concrete and steel. Bridge failure causes due to earthquakes are mainly overall results in affecting around 5 percent of the bridge failure in the United State [9]. In spite of the critical earthquakes did not happen near extensions over the last three decades, disappointment still rise because that the failure of principle fortifications was not perceived up to this point. It was first perceived in 1978 Miyagi-ken-oki earthquake when a few scaffolds endured harm at their docks. It was again perceived in 1982 Urakawa-oki seismic tremor when Sizunai Bridge endured broad harm at their docks [Asanuma]. The structure code was improved in 1980 by lessening the admissible shear worry of concrete and improving the advancement of fundamental bars. Different examinations have been led for assessment of the seismic hazard and retrofit of the untimely shear disappointment [10]. Due to the lack of the failure mechanism of the bridge piers during earthquakes, this paper focuses on investigation this failure mechanism and the dynamic response of such important elements (i.e. bridge piers) under semi-sinusoidal waveform under 1-g shaking table tests. A serious of shaking table tests are conducted using different cross-sectional bridge piers area (shape) to assess the seismic behavior and structural dynamic response of bridge piers as well as the dynamic earth pressure in front of the face and along the bridge piers underneath the ground surface.

2. Experimental methods

2.1 Materials

2.1.1 Soil Properties

The soil used as a foundation in the physical model is a sandy soil of golden yellow manifestation (silica sand). The properties of the sand which used in the actual study are cohesionless soil which was very
close to the HST95 silica sand’s properties, ordinarily used by researchers in various laboratories about the world [11, 12].

First of all, the sand was dried. Then, it was sieved on #10 sieve to remove the particles that are large in size and save in a dry place to be used in the model preparation using pluviation techniques. The air pluviation technique is widely used around the world for sandy soil preparation. To use the same density characteristics, specifications and the behavior of cohesionless soils that will be used as a foundation for the bridge pier model, some necessary steps should be taken in the laboratory. In order to achieve this purpose, the soil specimen must be reconstituted to its natural state. Sample preparation techniques can be influenced on fabric and stress-strain response of the soil particles. The air pluviation method is used extensively for preparation of large, uniform repeatable sand bed of desired densities for laboratory studies in order to achieve in-situ conditions and get suitable results which are highly reliable. The mechanical pluviator which manufactured by Aldefae et al, 2018 [13] consist of v-shape movable container and has pulley wheels and moving back and forth on frictionless bar’s guide and the soil (sandy soil) falling down from an opening (slot) in the bottom of the contained (hopper). As the relative density of the cohesionless soil is strongly influenced by the falling height, thus the pluviator contained a designed rope crane and attached to the main frame so that the container can be raised up and down to achieve the desired height. This mechanical pluviator can achieve uniformly sandy layer with relative densities vary from 28% to 71% and this range represents threshold of loose to dense state of the sand. The details of this v-shape container; the pluviator with the rope crane of mechanical movement are shown in figure 1.
2.1.2 Concrete properties

The materials in the synthesis of the concrete blending, in which used in the preparing the bridge piers models consist of ordinary Portland cement, fine aggregates, coarse aggregates and water. The specification of concrete blend design is $W_w = 210 \, \text{kg/m}^3$, $W_c = 300 \, \text{kg/m}^3$, $W_s = 450 \, \text{kg/m}^3$ $W_{agg} = 900 \, \text{kg/m}^3$ (i.e. C/R 1:1.5:3).

Firstly, the coarse aggregate was crushed. Then, it was passed on #6 sieve and retaining from #30 sieve and the fine aggregate passed on #6 sieve. The result of compressive strength tests appeared that the rate compression strength of concrete is 22 MPa for 28 days age of samples. Figure 2 shows the details of the procedure followed in concrete preparation.

2.2 Bridge pier modeling

In this study, laboratory physical models were performed as shown in figure 3 which simulates existing bridge piers sections in reality, proportional to the size of shaking table machine. There are six kinds were prepared for an extensive experimental study to investigate the seismic performance and dynamic response of bridge piers. Only two kinds were tested in this paper that will explain later in next section.
Figure 3. The bridge pier models sections

2.2.1 Preparing of small scale bridge piers

The cork framework molds were manufactured from cork block with (3cm) thickness that resembles the shape of the bridge piers that will be casted. A steel plate with (2mm) thickness was used in order to fix screws which are bearing the deck slab. Once the formworks are intended, the casting using the concrete mixture was done. The molds must be placed on the vibration machine to assure that the concrete mixture arrives all parts of the molds as illustrative in figure 4.

Figure 4. Casting of the concrete bridge piers models

2.3 Shaking test model preparation

The bridge pier models were left for 28 days curing time before using them in the model. A uniaxial earthquake simulator was used in the model testing under strong motion and pluviator machine was used for sand model production using air pluviation technique. Test the bridge piers under strong shaking in case of fully saturated (i.e. as in situ or prototype scale) including many types of sensors were performed. MEMS accelerometers for recording the respond acceleration, the earth pressure two linear variable differential transducers, LVDTs. Five Accelerometers (ACC) Which are distributed in different places in the soil and at the top of the bridge pier, three dynamic soil pressure sensors in front of the bridge pier face and two displacement transducers (LVDTs) in the vertical and horizontal direction as illustrative in figure 5.
He loads in the prototype scale above the bridge pier model were simulated and represented in the models scale, which came from the weight of the deck, girders, cross beam as well as the live load with a total load $q = 5$ kg.

3. Experimental results.
This study is conducted to investigate the dynamic response of concrete bridge pier built on saturated sandy soil. The model was prepared in a medium dense state using the pluviation technique. The thickness of the sandy layer was 55 cm. All instruments were fixed after the airing of the sand in the container that was design previously for this shaking table. The saturation process takes two days and the water moves from base of the model to the surface (i.e. small valve is made close the bottom of the container and external water tank is used and the water moves slowly through small tube from the tank to the model for 48 hrs.). In this case, the saturation does not effect on the initial stresses of the soil body and simulate the real saturation phenomenon for soil layers.

Figure (6) shows the front view of the bridge pier-soil model before the test with the distributed instruments in the model. It can be seen clearly the saturated sandy soil in the container and all the distributed transducer’s positions.

Figure 5. Shaking table model layout with instruments, all dimensions in cm.

Figure 6. The saturated bridge pier-soil model.

3.1 The input motion
To accredit the input motion for all the two shaking table tests, one of the accelerometer was fixed at the base of the container and the recorded wave is used as an input motion for the model. Thought the
shaking table is designed to produce only the sine wave form, but it was observed from the measured value of the accelerometer at the base of the container that there are tens other frequencies appeared during the shaking. In fact, these frequencies are very useful for representation the actual or real earthquake. Real earthquakes have hundreds of frequencies and the simulation of this need to use a geotechnical centrifuge apparatus. So, it was fortunately to capture many frequencies during the shaking tests as shown in figure 7.

Figure 7. Time-acceleration and frequency domain of the input motion.

4. Results and discussions.
4.1 The dynamic response
The dynamic response of the bridge pier-foundation model is assessed from the measured acceleration for both the soil (as a foundation for the bridge pier) and the bridge pier itself. Figure (8&9) shows the measured accelerometers in these tests. The Acc.1 refers to the input motion (the accelerometer at the base of the container). Acc.2 was fixed beneath the bridge pier. Acc.3 was fixed at the left side face of the bridge pier. Acc.4 was fixed far away from the bridge pier at the left side (close to the ground surface) while Acc.5 is tagged at the bridge pier model crest.
It was clearly shown from figure 6 that the measured acceleration from Acc 2, 3 and 5 in which they were very close to the pier are exited due to cyclic movement of the pier during motion and there were a positive permanent amplitude at the end of the shaking. This can be attributed to the inclination of the instruments as they are for uniaxial measurement and this behavior due to accelerometers deviation because of the rising up of water pressure. This shaking leads to liquefaction phenomenon and it was very clear in the failure mechanism that will be explained next section.

There was no large difference in the measured acceleration for model 2 (using chamfered bridge pier) as shown in figure 8. High amplification at the top of the bridge pier and attenuation is noticed for the accelerometers in which they fixed close to the pier. It could be worth to calculate the spectral acceleration (besides the frequency domain motion) as it was very difficult to see how the waveform effect on the piers using the time-domain, so, the spectral acceleration will be discussed next section.
4.2 Seismic displacement

Two linear variable differential transducers (LVDTs) are used distributed as shown in figure 5; one to measure the settlement of the bridge pier at shaking, during and post shaking stage while the other to measure the cyclic horizontal displacement during the shaking (which they were connected to the data logger). The lvdt's were fixed to measure the settlement and the horizontal displacement of the bridge pier during the shaking. Wooden bars are used, where they are fixed at the long direction of the container where the lvdt's were connected to prevent any undesirable movement of the lvdt's particularly during the shaking. The seismic displacement for the bridge pier was assessed from the measured vertical (settlement) from the lvdt's fixed on the crest of the bridge pier model. As shown in figures (10, 11), the settlement of the bridge pier model is strongly influenced by the effected shaking intensity. The maximum limits of the lvdt is 10 mm (i.e. from t=0 to t=1.7 s). The bridge pier model starts to settle after the exited time, 1s. During the shaking test, the effected shaking time is just around 1.7 second and during this time, the bridge pier is sunk down in the soil. Moreover, the bridge pier model at (t=1.7s) is turned over and because the length of the lvdt's needle is only 10 mm, it was very hard to measure the vertical movement (i.e. the settlement) at the remaining time (i.e. from 2s to the end of the shaking time). The horizontal cyclic displacement is measured also using the second lvdt. It was clearly shown that the cyclic behavior of the horizontal displacement followed the similar shape of the settlement except the limit of the lvds was 50mm. The peak cyclic horizontal displacement was picked up when very close to the time when the bridge pier model started shaking (i.e. t=0) and due to an excessive
applied motion that applied to the model, the bridge pier model needs only 2 seconds to be overturned and completely failure.

Figure 10. The settlement and the horizontal cyclic displacement of the aerofoil bridge pier

Figure 11. The settlement and the horizontal cyclic displacement of the chamfered bridge pier

4.3 The failure mechanism
The failure mechanism for the bridge pier model during the shaking test is inspected carefully. Figures (12,13) shows the subsequent consecutive image which were taken from time $t=0$ to time $t=12$ second (represents the exited motion that made the model fails). It should be noticed that the concrete aerofoil bridge pier model failure exactly similar the chamfered bridge pier failure. However, the bridge pier dived down after 1 second from the beginning of the shaking. This can be attributed to the pore water pressure generation which leads to occurring of the liquefaction phenomenon. Sudden drop in the strength and the stiffness for the soil underneath the bridge piers due to high rising of the pore pressure is the major reason of such failure.
Figure 12. Sequences of pictures during the exited motion of the aero foil bridge pier model

Figure 13. Sequences of pictures during the exited motion of the chamfered bridge pier model
5. Conclusions.
This paper included investigating the seismic behavior of concrete bridge pier model under strong shaking waveform by performing of two shaking models test on concrete bridge pier model while the seismic response and displacement of the bridge pier model were inspected during shaking. The main conclusions are summarized below:

- The amplification of the seismic waves is greatly increased from the base of the bridge pier to its crest, where the maximum amplification occurring at the crest region of the bridge pier model. Therefore, the design of this part of the concrete bridge pier requires great care and accuracy.
- The liquefaction phenomenon (because the rapid increasing in the pore water pressure due to cyclic loading) is generated when the bridge pier is founded on medium saturated soil which leads to specific failure underneath the bridge pier model.
- The failure mechanism in both test-1 and test-2 was overturning about one of the heels of the bridge pier.
- In the experimental data for both vertical and horizontal displacement curves, it has been observed that the reading of the instruments (i.e. LVDTs) have been reached to the maximum limits 2 seconds after the motion starting due to limited.

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