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Research paper

Seismic performance of concrete dam-reservoir system

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Abstract

This research is devoted to experimental work on the dynamic response of concrete gravity dam (small scale model under 1-g) taking into account the dam-reservoir and the dam-foundation interaction using the earthquake simulator shaking table which was designed and manufactured for this purpose. A 1-g dam model tests are performed and the soil foundation underneath the dam model was prepared using an air pluviation technique to obtain the relative density of 55% (medium dense soil). Many specific instruments were used: accelerometers, lvdts, pore water pressure and dynamic water pressure to measure different parameters during shaking. Two cases of tests were conducted: i) Dam built on saturated cohesion-less soil (test-1) and ii) The filled with water dam model (test-2). The seismic behavior is investigated during shaking (i.e. dynamic response and the seismic displacement) and the failure mechanism is inspected during the shaking. It was concluded that the case where the dam was filled with water is more stable during shaking that the other case and the failure mechanism is totally different. (I.e. sliding and overturning failure). The acceleration response spectra and the pore water pressure are measured and analyzed as well.

Keywords: *Shaking Table; Dynamic Response; Sand; Spectral Acceleration; Dam.*

1. Introduction

Dams are one of the most important infrastructure projects and a major economic supplier to countries. Concerns about their safety have been increased in a seismic environment over the past few decades, as earthquakes may impair their proper functioning and cause catastrophic failure to damage property and loss of life. Concrete gravity dams are huge solid structures, maintain their stability against exposed loads through geometric form, mass and the strength of concrete. Construction of gravity dams has a lot of advantages such as flood reduction and protection, water storage, electric generations…etc.

The response of the gravity dam structure to the ground vibration is a function of the nature of foundation soil; materials, form, size and mode of construction of the structure, the duration and the intensity of ground motion. The impact of seismic waves on dams depends on two main factors: the type of dam and the basis of the dam. There are many examples that illustrate the damage caused by ground vibrations on dams. In 1967 Koyna dam which is located in India was affected by an earthquake with PGA of 0.49 which is located in India causing serious cracks at a level 36.576 m below the crest. Other dams that have been affected by earthquakes such as Sefir-rud concrete buttress dam in the northern Iranian province of Gilan, Hsinfengking Dam (China, 1962) and the Shih-Gang Dam in Taiwan.

Generally, the dynamic analysis of gravity dams is a difficult and complicated process, as it is influenced by two important factors: i) The interaction effect between dam-foundation as well as dam-reservoir and ii) The effect of hydrodynamic pressure acting on the upstream face of the dam, which can be considered as a main loading in the dam design process [1, 2]. The physical modeling process is one of the best methods in order to simulate real earthquake excitation through single frequency, sinusoidal waveform [3-6]. The dynamic response of the dams was studied by many researchers using shaking table tests [7], performed the dynamic response of concrete gravity dams using multiple water modeling approaches such as Euler, Lagrange and Westergaard. A series of shaking table experiments conducted on four 3.4 high plain concrete gravity dam models in order to study the sliding responses and dynamic cracking [8]. The dynamic behavior of concrete dams using the physical model process to grasp the failure mechanism of these structures under earthquake excitations is investigated by Rosca [9]. An experimental study on seismic behavior analysis of concrete dams, using small-scale models with scale factor of 1:30 (model: prototype) taking into account interaction effect between the dam-reservoir-foundation is presented by Resatalab et al. [10].

The objective of this paper is to investigate the seismic performance of gravity dam using scaled model, taking into consideration the effect of the dam-reservoir and the dam-foundation interaction. A series of shaking table tests were carried out with three several types of tests: i) Dam with an empty reservoir (dry cohesion-less soil), ii) Dam with an empty reservoir (saturated cohesion-less soil) and iii) Dam with full reservoir water. A special measuring equipment were also used to figure out this behavior and the failure mechanism.

2. The physical modelling of the dam

Principles of the physical modeling in geotechnics is followed and implemented proportional to the size of shacking table machine as shown in figure 1.

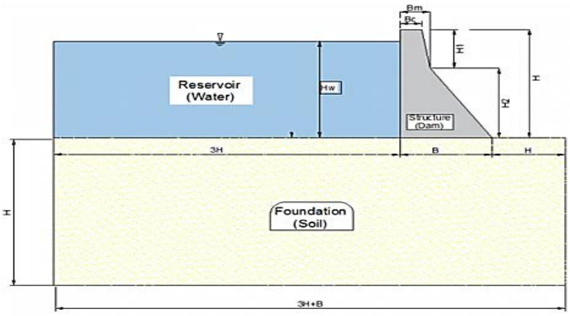

Fig. 1: The Geometric Dam Model.

It can be seen that the dimensions of the dam model are selected based on the limited width of the container. The dimensions of the container are (600 mm width, 900 mm length and 850 mm height), with one transparent side made from glass (10mm thickness) to monitoring and inspecting the soil-dam behavior during the shaking. It was designed based on the shaking table dimensions and all the interior dimensions are provided with a10mm special rubber layer to decrease the reflection of the wave propagation in both water and soil during the shaking. Full details of both the shaking table and the container are found by Asad and et al. [11]. Table 1 shows the dimensions of concrete dam model and the geometry of the tests.

Table 1: Model Dimensions of the Dam

Variables	Dimensions (cm)
H	40
B	27
H_w	36
H1	14
H2	26
B_c	6
Bm	8

3. The material properties

3.1. The soil

The soil that is used as a foundation of the physical model is a sand of golden yellow appearance. The properties of the sand are cohesion-less soil with similar properties to the HST95 silica sand. First, the sand was dried in the oven for 24 hours. Then, it was sieved in # 10 to prevent the crossing of large particles. Depending on USCS, that was investigated according to ASTM D9728 [15], the prepared sand was poorly graded sand with clay (SP-SC). The fundamental physical properties were determined in the laboratory in order to make a comparison with the properties of HST95 silica sand and HST50 Ottawa sand (see figure 2) that has been widely used in the University of Dundee [11], [12]. The physical properties of the sand used were shown in table (2) in addition to the properties of both HST95, HST50 silica sand and Ottawa sand.

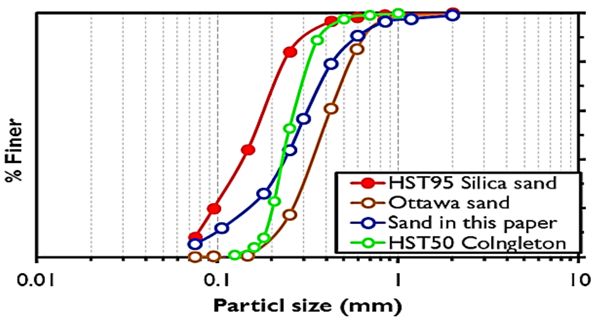

Fig. 2: The Grain Size Distribution of Used Sand.

Table 2: Physical Properties of Used Sand

The property	This sand	HST95 Silica sand	Ottawa sand
Specific gravity, G_s	2.67	2.63	2.64
Shape	Rounded	Rounded	Rounded
Mean particle size, D_{50}	0.28	0.15	0.32
Coefficient of uniformity, C_u	2.85	1.9	1.68
Coefficient of gradation, C_z	1.32	0.95	1.08
Minimum dry unit weight, $\gamma_{dmin}\ (\frac{kN}{m^3})$	14.8	14.7	14.9
Maximum dry unit weight, $\gamma_{dmax}(\frac{kN}{m^3})$	19.1	19.2	19.5

The technique that used to prepare the foundation base for the dam model is the air pluviation method. This method is well known due to ease of model preparation and could obtain a uniform soil layers. The relative density that can be determined from pluviation technique influenced by many parameters such as falling height, uniformity of raining sand and the particle characteristics [13]. Figure 3 shows the mechanical pluviator apparatus that was used in soil preparation in this paper.

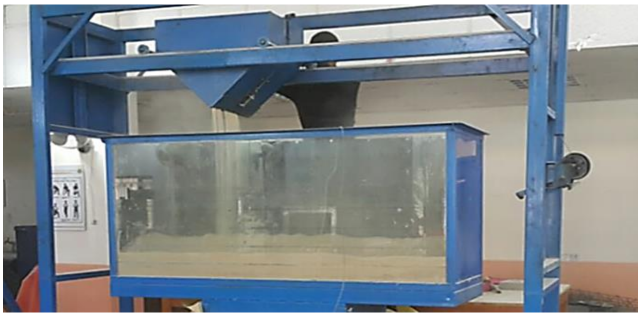

Fig. 3: The Mechanical Pluviator.

In this study, the relative density of 55% (medium dense soil) was used, based on 1 m container height and 3.5mm slot size. On the other hand, this density was compared with both Bertalote et al. [14] and Al-Defae et al. [11] as shown in figure 4.

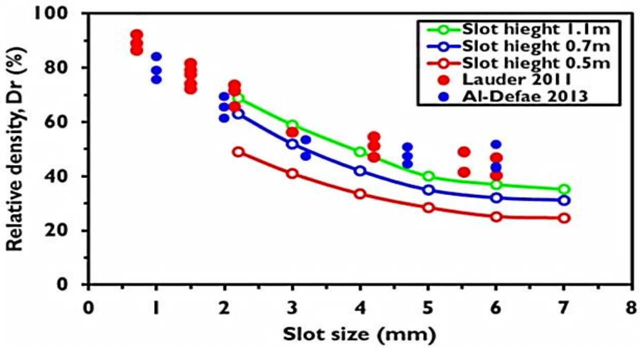

Fig. 4: Slot Size Correlation with Relative Density.

3.2. The concrete properties

The concrete mixture consists of ordinary Portland cement, fine aggregates, coarse aggregates, water and mixes them. The specification of concrete mix design is Ww = 150 kg/m^3, Wc = 300 kg/m^3, Ws = 450 kg/m^3, Wagg= 900 kg/m^3 and the amount of admixture differ from 0.2 to 3 liters for each 100 kg of cement. The coarse aggregate is crushed, and then passed on # 4 sieve and retaining from # 16 sieve to achieve the scaling properties as much as possible. The result of compressive strength specimen tests presented that the average compression strength of concrete is 26 MPa for 28 days old specimens as shown in figure 5.

Fig. 5: Slot Size Correlation with Relative Density.

3.2. The concrete dam model preparation

After finishing the design process, the special framework is designed and manufactured for casting the concrete dam. A small diameter holes embedded with plastic tubes (2.54mm) is made to leave space to install water pressure sensors with their wires as shown in figure 6.

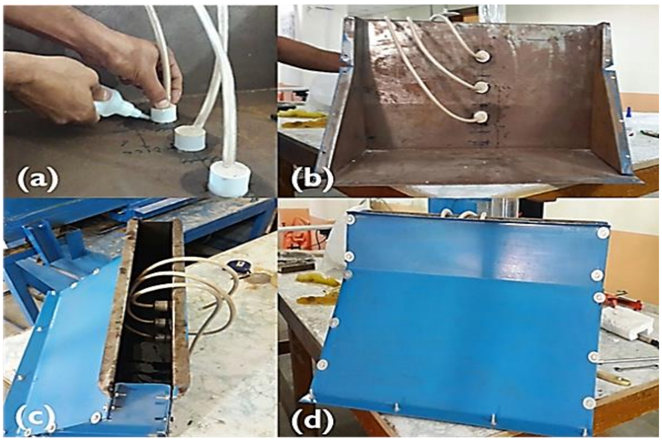

Fig. 6: Steel Framework and Sensor Holes Preparation.

The concrete mixture is prepared and axiomatic procedure is followed during casting of the concrete (see figure 7). One month is left for concrete curing before starting the tests and the water pressure transducers are fixed at the upstream face in the distinct holes.

Fig. 7: Concrete Casting.

4. The results of the model

In the current paper, two cases of model tests were conducted: i) the empty reservoir (built on saturated cohesion-less soil), where 3 acceleration sensors (within the soil as well as at the crest of the dam) and 2 displacement sensors were used and, ii) Dam with full reservoir water, as in the second case with addition of 3 water pressure sensors at the upstream side of the dam model.

4.1. Seismic dynamic response

4.1.1. The response of time-acceleration

The dynamic response of the dam-foundation model is evaluated by the measured acceleration of both soil and the dam, as shown in figure 8. The Acc.1 was fixed at the base of the container which refers to the input motion. Acc.2 was fixed at the upstream side far away from the dam, Acc. 3 placed at the crest of the dam model and finally Acc.4 is fixed below the dam to investigate the dam stability.

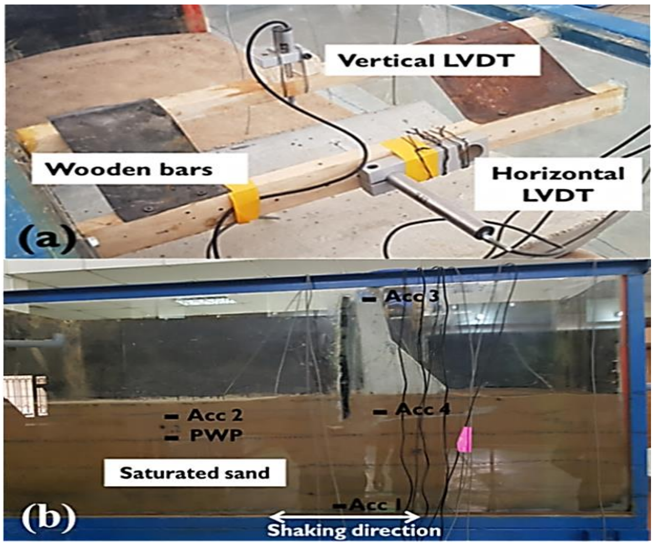

Fig. 8: Test 1; (A) LVDTs Positions and (B) Dam Model-Soil- Container.

Predominant single frequency input motion (i.e. 1.7 Hz) is used in both shaking test models. The motion has an amplitude 0.9 g and 10 second. Figure 9 shows the time-acceleration and frequency domain for this motion.

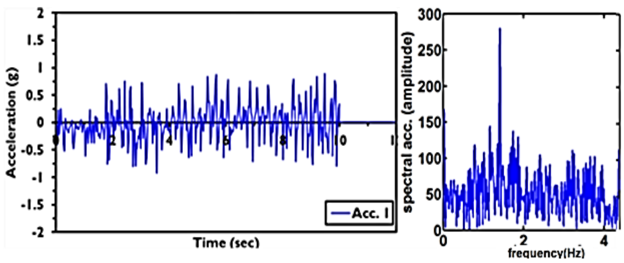

Fig. 9: Time Acceleration and Frequency Domain of Input Motion.

Figure 10 shows the time-acceleration and frequency domain measurement when the soil is fully saturated (i.e. test 1). A slightly amplification was noticed in the reading of ACC.2 (at the upstream side close to the soil surface) which equal to 1.05g which is contrary with the amplification that was noticed by many studies due to topographical amplification [14, 15] (g=1.68) in dry model, with the predominant frequency approximately 1 Hz. This small amplification was occurred due to fact that the saturated soil particles absorb the wave of acceleration whereas this is contrast with case of dry soil layers (i.e. the amplification factor may reaches to 1.6). Also, the measured acceleration of the accelerometer sensor below the dam model (ACC.4) was noticed has a low amplitude (g=0.5) which is equivalent to about 45% from the input motion (g=0.9). This large attenuation was occurred due to the heavy weight of the concrete dam model, which prevents the soil under the dam to be vibrated as the other accelerometers in another position.

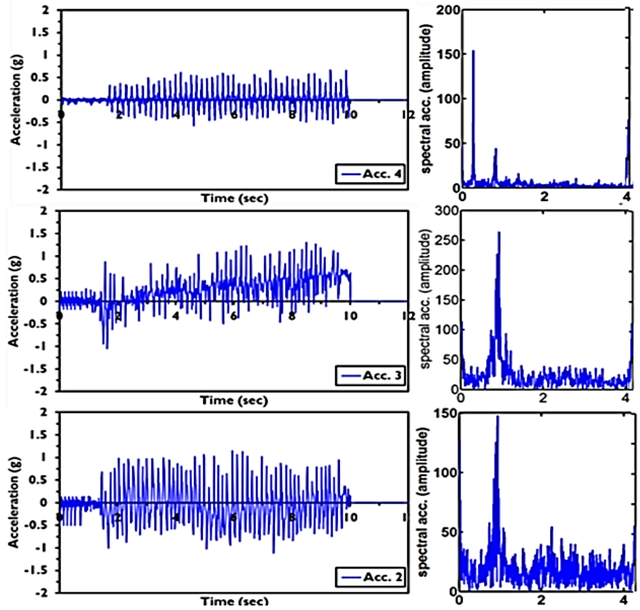

Fig. 10: Time Acceleration and Frequency Domain of Empty Dam Model (I.E. Test 1).

It should be noticed also that the acceleration output at the crest of the dam model is too high (i.e. 1.4g) and this is not surprising as the dam trends to be overturned due to intensity of the shaking and this will be explained in the next section (failure mechanism).

Figure 11 shows the acceleration measurement in case of full reservoir. A red line is added to the graph (in ACC.2 and ACC.3) that represents the average values for the data. It can be seen that there is a noticeable attenuation for the acceleration measured by Acc. 2, due to the weight of the water at the upstream which prevents the wave from propagation, making large amplitude cyclic motion (or the hysteretic) at this zone. The acceleration measured at the crest of the dam model (i.e. ACC.3) shows a hysteretic acceleration response for the concrete dam model. This occurs as a result of the cyclic wave pressure, which is generated at the face of the dam in the upstream and vice versa (i.e the dam model movement at the direction of the upstream). Also, the dynamic response of ACC.4 (below the dam model) is similar to the previous test and this is due to the heavy weight of the model itself. On the other hand, the heavy weight of the water and the dam model preventing with fully saturated state, as a result, the possibility of the phenomenon of liquefaction was reduced or it was not visible to be noticed during shaking.

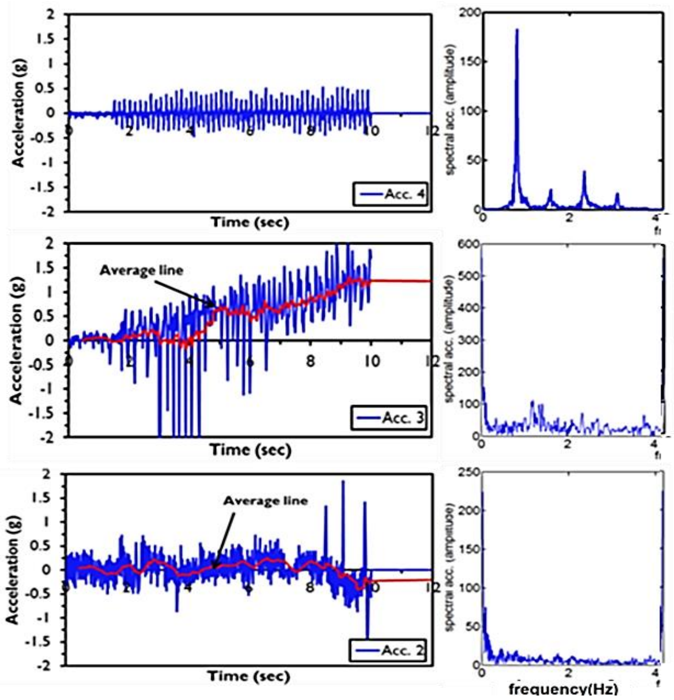

Fig. 11: Time Acceleration and Frequency Domain of Filled with Water Dam Model (I.E. Test 2).

4.1.2. The acceleration response spectra (ARS)

Based on Eurocode 8 (EC8, design of structures for earthquake resistance, Part 1), the acceleration response spectra (ARS) for the ACC.1, ACC.2, ACC.3 and Acc.4 were presented (for 2 second only as the dam model is not strongly affected by the last 2 seconds of the spectral acceleration).

The acceleration response spectra for the empty saturated model was described and plotted in figure 12. The period that must be taken into consideration in the design of such a structure (i.e. concrete dam model) that is built on saturated soil is ranging between 0.2s (5Hz) and 0.04s (25Hz). It can be noticed that both the accelerometer at the upstream far away from the dam and at the crest of the dam model have clearly exited due to cyclic motion. Also, it can be observed that the response of the accelerometer underneath the dam has not been much excited. This is because of the cyclic stress due to shaking at the position where the heavy weight of the dam has restricted the shaking. Furthermore, the dynamic response for the dam model that was built on saturated cohessionless soil has less effect than the previous test when the dam model was constructed on dry cohessionless soil (not shown in this paper) for two main reasons: i) The cyclic stress – strain behavior for the voids ratio that was filled with water has less triggering to shaking compared with voids filled with air and ii) The large density for the saturated soil comparing with dry soil state.

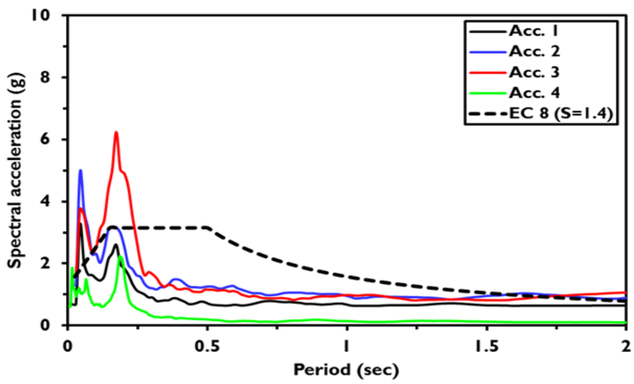

Fig. 12: Effect of Shaking on the Acceleration Response Spectra (Empty Test 1, 5% Structural Damping).

The acceleration response spectrum for test 2 is shown in figure 13, which is relatively different from the previous test. It can be observed that the ARS (i.e elastic response spectrum) exceeds the limitations of the EC8 for a very low period (i.e. less than 0.15 second) and at high period (i.e. 1.2s). This means that the frequency ranges above 7Hz and below 0.8 Hz. On the other hand, the dynamic response of the Acc. 4 (which is located a few centimeters underneath the dam) is still under predicted with the limits of the EC8.

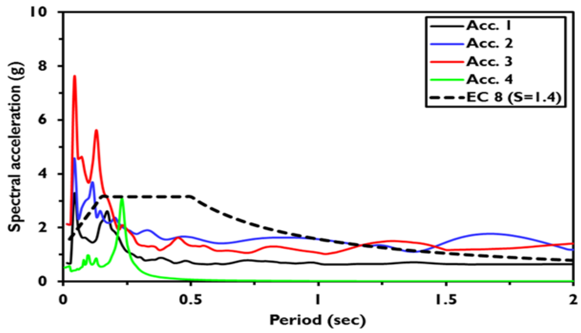

Fig. 13: Effect of Shaking on the Acceleration Response Spectra (Filled with Water Test 2, 5% Structural Damping).

4.2. The seismic displacement

The measured displacement for both the horizontal and the vertical displacement are illustrated in figure 14 and 15. In case of the empty dam, the dam model requires to only 1.9 second from the shaking time to reach to 10mm (green line) thus, it was stiff curve and this can be attributed to the fact of losing the stiffness and the strength of the saturated cohessionless soil underneath a devastating shake in a very short time because of the generation of pore pressure. In this case, the soil cannot withstand the pressures resulting from the dam load, where the effective pressure is reduced to the minimum value. The cyclic horizontal displacement also has similar behavoir to the input motion with an equilibrium in the shaking behavior between positive (refers to the downstream direction) and negative (in the upstream direction) displacement because of the sudden settlement of the dam model into the soil. Moreover, the dam model was settled into the soil due to reorientations of the soil particles in saturated state as well as the liquefaction phenomenon.

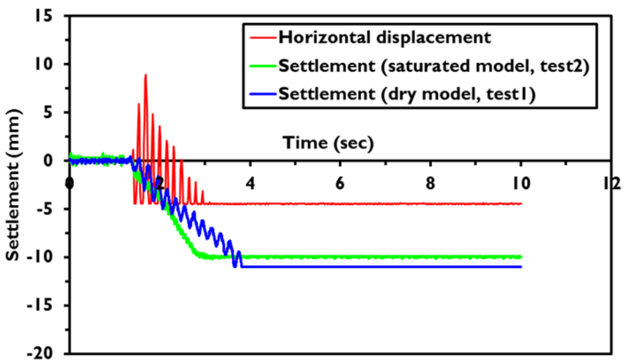

Fig. 14: The Measured Horizontal and Vertical Displacement for Saturated Soil-Dam System (Test-1).

The seismic displacement (both of horizontal and vertical displacement) of the filled with water-dam model in test 2 shown in figure 15, which is totally different from the previous cases. It can be noticed that there is only positive displacement which represents the movement of the dam model (sliding) towards the downstream side because of the kinematic energy of the water (i.e hydrodynamic pressure) generated at the upstream face of the dam model. The final horizontal displacement was accomplished at shaking time little bit more than those at the test-2 (empty saturated model) which was around 3 s. The vertical displacement (settlement) for the dam model does not much differ from the values in the other test. However, the measured settlement is 8mm after 3.6s and remains constant until the end of the shaking time due to limits of the LVDT.

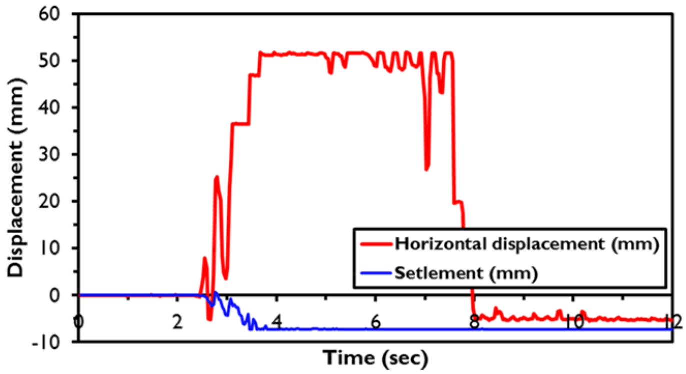

Fig. 15: Seismic Displacement and Settlement of the Dam Model (Test-2).

4.3. The pore water pressure in test 1

The pore pressure that was investigated at the upstream direction far away from the dam near the surface is measured using pore pressure transducer with a 10 kPa limit. The measured pore pressure at similar beginning time of the exited motion (i.e. 1.32 sec), as shown in figure 16. It can be noticed that a considerable pore pressure is developed under the water bed level at a medium shallow depth. On the other hand, the pore pressure remains constant until the end of the shaking time and took the same motion behavior.

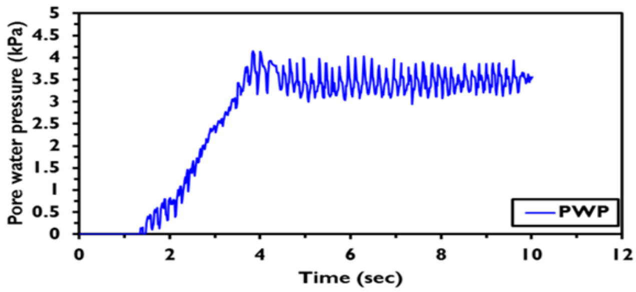

Fig. 16: The Measured Excess Pore Water Pressure (Test-1).

The dynamic water pressure (i.e. the cyclic water pressure during shaking) was measured using the transducers of water pressure (ranging between 0 to 10 KPa), which are installed in a vertical line at the upstream face of the dam model as shown in figure ١7. It was clearly shown that the cyclic water pressure increases at the top section of the dam, this due to higher waves of water. While it decreases at the deepest transducer (i.e. red line). On the other hand, the measured water pressure at the bottom section of the dam model is relatively bigger than the middle one (especially after 6 second shaking time), because the opposite cyclic wave of water.

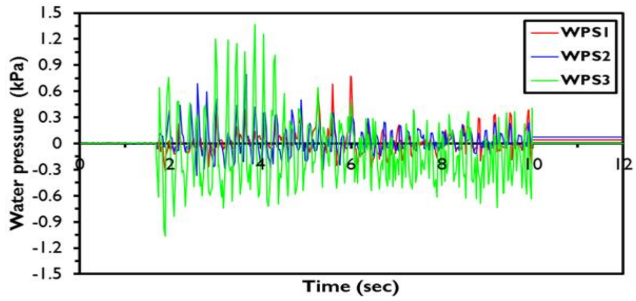

Fig. 17: The Measured of Water Pressure at the Face of the Upstream.

4.4. The failure mechanism

The failure of the dam model in case of empty can be observed by the sequences pictures for 10 second in figure 18. It can be noticed that the dam model has not completely failed (i.e. overturning failure about the heel or slides) as occur in most failure mechanism of the dams, and it was observed that only 20º inclination. On the other hand, the dam dives into the soil after 2.86 second from the starting of the shaking. This failure mechanism of the dam model can be attributed to the of pore water pressure generation which causes the liquefaction phenomenon in the soil after first 3 second of shaking. However, the liquefaction phenomenon usually leads to failure for the infrastructures without damage in the structural elements because of the loss of the stiffness and the strength; due to rising of the pore pressure (i.e. the effective stress will be very low).

Fig. 18: Sequences of Pictures during the Exited Motion (Test- 1).

The failure mechanism of the dam model filled with water is completely different from the previous test due to the presence of hydrodynamic pressure force at the upstream face of the dam, which prevents the overturning failure from occurring. Instead, the sliding failure mechanism is clearly shown in the dam model as in figure 19. It can be observed that the final sliding displacement for the dam model at the end of the shaking is equal to140mm. In order to determine the final displacement of the dam model, pen marker is used at the transparent face of the container to observe the sliding movement. The boundaries of the container are affected on the water wave at the upstream. On the other hand, the failure mechanism not highly influenced by the boundary effect because of the upstream length is more than two times of the dam width

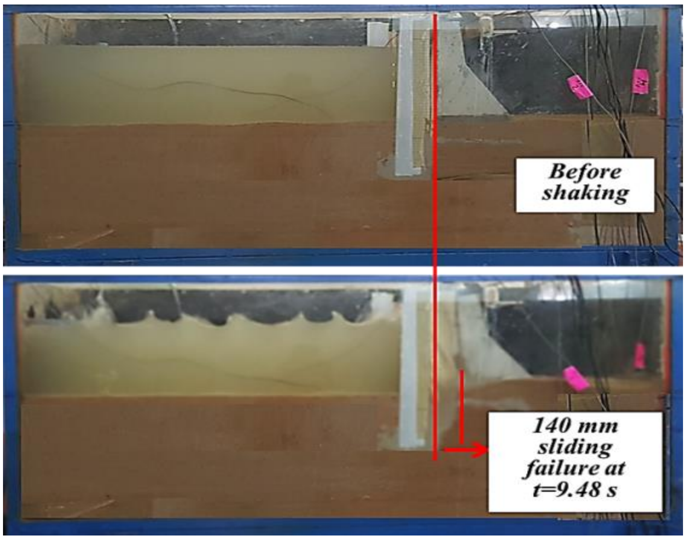

Fig. 19: The Sliding Failure of the Dam Model at the End of the Shaking.

5. Conclusions

In this paper, extensive efforts have been devoted to investigate the dynamic response of concrete gravity dam taking into account the dam-reservoir and the dam-foundation interaction using the earthquake simulator device. The main conclusions are:

1) The seismic wave is either damped or absorbed by the saturated soil particles. This was clearly demonstrated by reading the sensor ACC.2 in the saturated dam model compared with dry model.
2) There is a massive amplification in the first test for the reading of acceleration sensor ACC.3 and becomes hysteretic in the last test. Therefore, maximum safety should be taken when analyzing and designing the upper part of the dam (the crest).
3) There is noticeable attenuation in the reading of acceleration sensor ACC.2 in both test-1 test-2, due to the heavy load of the dam model causing a restriction of the seismic wave.
4) The failure mechanism in test-1 and was overturning about the heel, while it was sliding failure in test-2, due to the effect of hydrodynamic pressure for water mass on the upstream face of the dam side.
5) Finally, there is a crazy response in both tests for the acceleration response spectra figures, this should be taken into account when designing the structural parts of the dam at that location (i.e mechanical parts, pathways and gates).

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