DEVELOPMENT OF AN EARTHQUAKE SHAKE TABLE FOR THE EXCITATION ANALYSIS AND PERFORMANCE EVALUATION OF STRUCTURAL MODELS

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Abstract: The study focuses on the development of an earthquake shake table for data and performance monitoring of a pre-designed structural base isolation system that will pave way to the structure's improvement of design through simulation of damping motion of the structural model in response to different earthquake magnitudes. The earthquake shake table gathers information on its test subjects by the use of attached structural seismometer sensors to calculate its damping motion and base shears, which are directly inputted to built-in monitoring software. The test subjects used for the experimentation process of the earthquake simulation table are two high-rise structure models, which were demonstrated with towers constructed with different materials evaluated through Buckingham pi theorem to replicate the most accurate results of an actual structure's excitation during an earthquake. The two test subjects differ in their structural foundation, one is structurally base-isolated and the other is conventionally base-attached. The integration to the study of the DPWH guidelines and implementing rules of earthquake recording instrumentation for buildings were the basis of the location of seismometers to the test models to ensure that standard earthquake recording methods are verified and accurately followed. The results of the working Titan Mk.III prototype features the excitation recordings of the test subjects via the system's accelerometers attached to the two structural test subjects combined with the magnitude produced by the earthquake shake table. The result of the test differs in the performance of the two test subjects wherein the base isolated-structure performed an average of 38.18% decrease in structural excitation compared to the other. To further improve the accuracy of the structural readings of the prototype, a 3D-rendered monitoring program is proposed to be integrated to Titans' data recording software to produce more aesthetically and user friendly results. In conclusion, the raw data and results produced by the third generation prototype of the earthquake shake table provides the comparative analysis of the two structures wherein it produces the actual excitation basis of the structural models that underwent certain ground motion simulations through the Titan earthquake shake table.

Keywords: *earthquake shake table, base-isolated foundation system, earthquake technology, earthquake engineering, structural engineering*

1. INTRODUCTION

The Philippines is categorized as part of the Pacific Ring of Fire, which consists of regions that are regularly experiencing seismic and volcanic activities. This means that the country of the Philippines is prone to infrastructure damages caused by natural disasters. The Philippine structures are underprepared for such calamities due to the lack of construction design methods of performance-based earthquake engineering in its infrastructures. This leads to destruction of these structures, hence, compromising the safety of the Filipino people against seismic activities. Establishment of performance-based earthquake engineering-designed structures in the country will amplify and expedite the solutions of earthquake engineers in a structure's reaction against ground movements. Usually, numerical computation methods for structural design and performance are used by structural engineers to counter the effects of natural seismic events. This is a common practice in structural design. However, limitations to this method can be encountered when it comes to implementing the application of additional new earthquake technologies to strengthen the structure's design. Since the implementation of new structural earthquake-resistant technologies requires actual prototypes in its development phase, and not to mention a testing facility for the test of its prototypes, engineers are discouraged from focusing on new methods in developing alternative ways to make our structures more seismic disaster-proof. This limitation affects our Filipino scientists in the way we can update our structural building codes and improve how our structures are built.

Earthquake scientists and researchers from developed and tech-oriented countries use equipment called an "earthquake shake table", which can simulate ground motions having different magnitudes with almost the same accuracy as a natural ground motion. The advantage of possessing such technology is that it enables earthquake scientists and structural engineers to test actual structural models and building components typically to its point of failure. Philippine's current struggle with seismic disasters is still high-tensioned, with the "Big One" still yet to occur due to the movement of the West Valley Fault, and numerous major seismic calamities strike from time to time. The country's infrastructure design improvements might give the structures enough time to prepare for the upcoming seismic disasters through seismic technology applications.

This is where the Ultra Construction Innovators' development of Titan earthquake shake table plays an important role. Ultra Construction Innovators, a private research group that focuses on development of construction technologies called their earthquake shake table "Titan" after the Titan Poseidon from Greek mythology, who is also known as the "earth shaker" titan for being the "god of earthquakes". For local development of earthquake technologies, the Titan earthquake shake table aims to pioneer the local earthquake testing facility or equipment prioritizing the development and authorization of such technologies. This is to showcase the advancements of the structural engineering capabilities of the country–embracing technological advancements to a primitive practice for the greater good of the general public.

2. METHODOLOGY

2.1 Research specifications

The proposal for the creation of the Titan earthquake shake table was first raised when the researchers from Ultra Construction Innovators cannot find an available earthquake shake table testing equipment to test their proposed seismic base isolation design for their undergraduate research. The undergraduate researchers, then, reached out to the Philippine Institute of Volcanology and Seismology (PHIVOLCS) and requested to use their earthquake shake table. However, the earthquake shake table available at their facility is not suitable for structural performance use, but rather, a novelty apparatus used to perform different levels of ground movements to be experienced by the person standing on the platform arranged in a home setup scenario. The researchers were also informed that there was not any available earthquake shake tables in the country that test structural models. However, they did mention that there was another earthquake shake table located in University of the Philippines-Diliman, College of Engineering, but it was still inoperative during the time the researchers conducted the consultation. With no earthquake shake table available to aid the researchers in their study, the researchers were left with no choice but to build their own apparatus.

2.1.1 2017 Prototype —Titan earthquake shake table Mk.I

The initial idea of the researchers was to create an earthquake shake table with a two-by-two feet wooden board platform equipped with four rollers while attached to a steel rod with a wheel axle at the end. The rollers were placed on a runway to keep the movements of the rollers in place during the shake tests. The whole contraption was powered by an electrical hand drill to be pegged to the wheel axle to produce the shaking motion of the platform. The downside of this version of the prototype is there was no way to monitor the ground movements to determine the level of magnitude applied to the shake platform; hence, the structural excitation of the structure cannot be calculated. Structural excitation is the ability to input significant energy into the structure, particularly, at higher frequencies. Although this prototype was not designed to give any kind of data to the researchers, the prototype still contributed to a local tower building competition in the Civil Engineering Department of the Holy Angel University by shaking the towers built from scratch by the University students, determining whose structures performed best during an unspecified ground shake produced by the prototype. The concept structural framing of this prototype has become the basis of future versions of the Titan earthquake shake tables.

2.1.2 2018 Prototype —Titan earthquake shake table Mk.II

The second prototype was immediately developed after the creation of the first prototype and debuted at the 2018 HAU School of Engineering and Architecture Technology Exhibit, an event where each department showcased its best technological research and projects made by undergraduate students. This time, a bigger platform was installed to the Titan earthquake shake table, a one-by-one meter shake platform equipped with nine rollers to handle heavier test models and to stable out the structural load during shake tests. Another improvement on this model is the 10-horsepower alternating current (AC) motor that runs the whole differential gear of the shake table.

The undergraduate researchers then reached out for the second time to PHIVOLCS to consult for the accuracy of ground motions of their single degree of freedom earthquake shake table prototype. The researchers were then introduced to the Richter Magnitude Scale by Dr. Rommel Grutas, a senior science specialist from PHIVOLCS. Richter magnitude scale assigns a number to quantify the amount of seismic energy released by an earthquake. He recommended applying the ground acceleration of each magnitude level of the Richter scale to the 2nd prototype of the Titan earthquake shake table.

To integrate the equivalent acceleration of the magnitude levels of the Richter scale to the prototype, a tachometer was installed to the differential gear of the earthquake shake table – monitoring the speed of the differential in rotations per minutes (rpm). An original conversion formula was then produced by the researchers, dubbed as the "Titan differential formula", to convert the rpm produced by the differential into meters/second squared ($\mathrm{m/s^2}$) to match the units of the Richter scale in a single degree of freedom. Once the speed can be monitored, the researchers needed to control the speed output of the differential gear to match the given magnitude acceleration of the Richter magnitude scale. This was done by installing a speed regulator to the AC motor that connects to the differential gear. The final requirement to ensure the accuracy of the replicated ground shake produced by the shake platform was the installation of digital seismometer sensors. Seismometers would allow the researchers to measure the replicated ground movements by converting vibrations from the platform shake movements, which can be displayed as seismographs on the computer screen. These were placed under the isolated center portion of the shake platform. To monitor all of the running components of the Titan earthquake shake table, a separate control board was added to the system.

Figure 1. Researchers work on the wooden frames of the 2nd version of the prototype (left portion); the 1st version (lower right) is sitting beside the improved version. Photo shows the size difference of the two prototypes.

Figure 2. A fully operational Titan earthquake shake table (left) and its control board (right).

2.1.3 2020 Prototype—Titan earthquake shake table Mk.III

Two years after the creation of the second prototype, the third version of the Titan earthquake shake table was developed. It focused more on the software upgrades of the prototype, sensors and seismometers for its hardware, and improvement on platform size and freedom of movement.

To capture a much more elaborate structural excitation of the test model structures, the third prototype model of Titan earthquake shake table added three structural seismometers connected to the prototype's own earthquake recording instrument (ERI). This was based on the "DPWH Guidelines and Implementing Rules of Earthquake Recording Instrumentation for Buildings" for the case of earthquake recording instruments on high-rise structures such as private and other buildings above 50 meters high. There should be an installation of three Earthquake Recording Instruments (ERI) for structural health monitoring and each should be located at ground floor/lowest basement, middle floor, and floor below the roof.

Figure 3. Ultra Construction Innovators' head researcher runs a calibration test on the newly improved control board of the the third prototype of the Titan earthquake shake table.

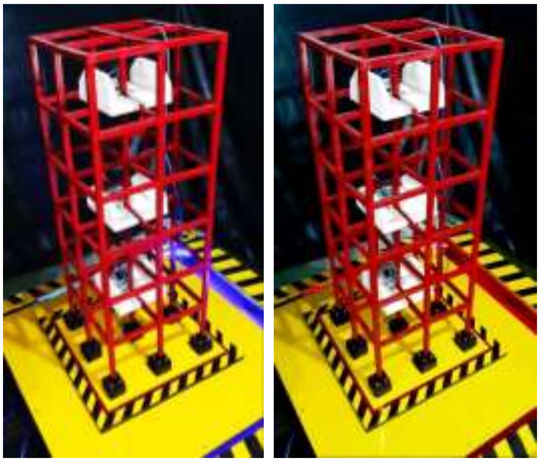

Figure 4. A set up of a structural model on the shake platform fully installed with Titan's accelerometer sensors. Three accelerometer sensors are installed on the bottom level, middle level, and on highest level as per DPWH guidelines. Left photo shows standby mode (blue light); right photo shows (red light) active/shake mode of the apparatus.

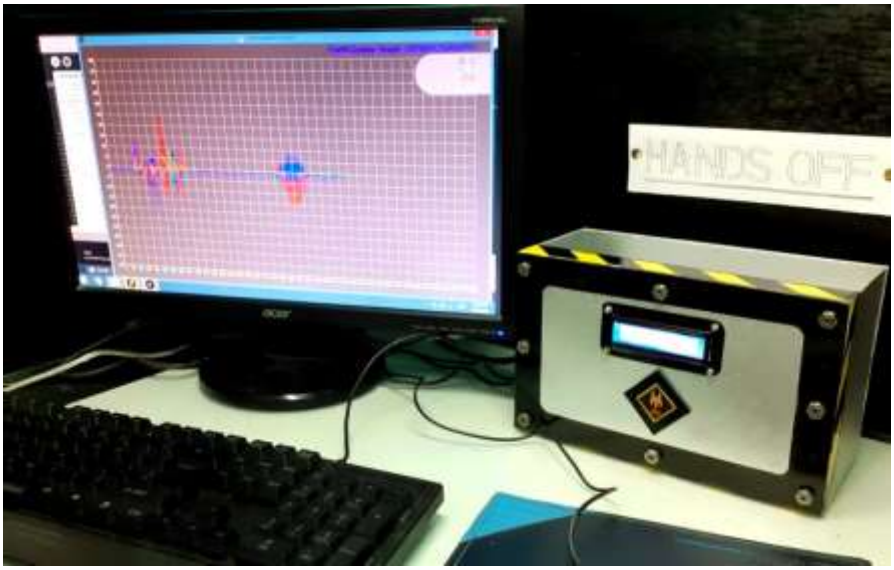

Figure 5. Titan earthquake shake table's own earthquake recording instrument "ERI". The seismograph content on the screen (blue, red and green) are from the three seismometers installed on the structural model.

Figure 6. Ultra Construction Innovators' head researcher conducts an earthquake simulation for a 5-storey structural frame fully equipped with the seismometers of the Titan earthquake shake table.

2.2 Research design

A quasi-experimental design was used in the study as the source of basis in certifying that the created prototype is acceptable in terms of its accuracy and effectiveness in determining the magnitude. This type of experimental design consists of two selected participants where one receives an intervention and the other does not. In this manner, the treatment given can be measured quantitatively. The study conducted determination of magnitude using the Philippine Earthquake Intensity Scale (PEIS), a seismic scale used and developed by PHIVOLCS to measure the intensity of an earthquake and seismograph as stated by the PHIVOLCS for the testing of the prototype's capability to produce certain magnitude levels. Thus, the study can be categorized as a quasi-experimental design. A minor descriptive-qualitative research method was also conducted by means of a survey due to the need to evaluate the efficiency of the prototype, which the researchers chose to take the study's beneficiaries' opinion as basis for result. This was necessary to acquire a qualitative evaluation of the research's final result.

2.3 Data gathering

Experimentation data gathering–The study involved the "classic" experimental design. Laboratory and quasi-experiments were conducted for the development of the test subjects—the base isolation system for proving its efficiency against structural excitations.

Cross-sectional design–The study's data gathering also involved the cross-sectional design due to the inclusion of the information obtained from PHIVOLCS when the researchers visited the government agency and took the advice on the development of the prototype.

Longitudinal design–The study's data gathering also involved longitudinal design, which included the data collected from previous earthquakes in terms of structural failures and casualties that would be simulated in the test subjects of the prototype.

2.4 Procedure

1. Data gathering
   Gather information from previous data on recent major earthquakes that happened in the Philippines. Input to the system the information on the ground motions that occurred in the area, casualties, and economic damages.

2. Software input
   Input the target earthquake ground motion to be replicated on the system of the Titan earthquake shake table.

3. Test subject
   Test the two subjects on the replicated earthquake ground motion. Both test subjects will undergo the same rate of ground motion; the only difference is that one of the test subjects is applied with the designed structural earthquake resistance base isolation system while the other is a conventionally built structure.

4. Real-time monitoring of data input
   Monitor the real-time performance of the test subjects through the accelerometers' sensors connected to the Titan earthquake shake table system while ensuring the accuracy and effectiveness of the ground motion produced by the prototype. Identify the errors and make necessary adjustments.

5. Assessment and conclusion
   Evaluate the results of the experiment.

2.5 Titan earthquake shake table

The proposed earthquake shake table to be used in this study is the third generation prototype of the shake table series. This particular prototype model compared to its predecessor models has additional structural accelerometer systems sensors for more accurate structural excitation recordings.

2.6 Test subjects

The two test subjects are designed identically except with the foundation portion of the structure. These are full rebars that were built to undergo Buckingham pi theorem computations, a key theorem in dimensional analysis. It is a formalization of Rayleigh's method of dimensional analysis to capture the realism of weight to size scaling of the structure for a realistic structural reaction.

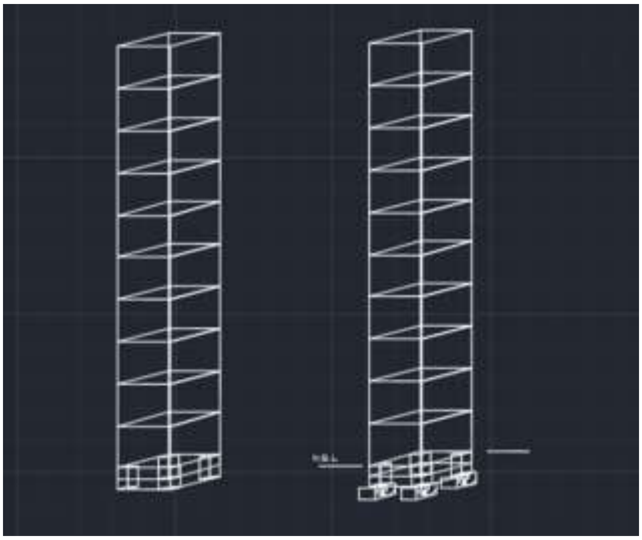

Figure 7. The difference between the two structural models. The structural model on the left is the conventional foundation fixed on the ground while the structural model on the right is the base-isolated installed structure.

2.7 Seismometer sensors

The seismometer sensor that was connected to the Titan earthquake shake table control board was installed at the ground floor, middle floor, and highest the floor. Three installed sensors would be enough to cover a high-rise structure as stated in "DPWH Guidelines and Implementing Rules of Earthquake Recording Instrumentation for Buildings". The accelerometers sensor of the Titan shake table also integrated the Richter Magnitude Scale into its software. Moreover, a conversion is needed to match the energy produced by an earthquake to the one that causes movements of the platform as an output.

Figure 8. Self-righting diagram of the base isolation installed in one of the structural models.

3. RESULTS AND DISCUSSION

The data results produced by the earthquake shake table are in seismograph format. Data were obtained from the three accelerometer sensors attached to each structural test model as the platform shakes actively with increasing magnitude for 1 minute and 30 seconds to capture the excitation reaction of the modeled structures. Below are the seismograph readings of the two test structures from the experiment.

As shown in Table 1, the average acceleration of the conventionally built foundation structure model that underwent 90 seconds of ground shake simulations is 1.1 m/s^2 while the base isolation-equipped foundation structure model that underwent the same duration of test has a 0.68 m/s^2 of acceleration. The data showed that there is a 38.18% decrease in structural excitation with the use of the designed base isolation foundation on the structural model compared to the use of conventional foundation design.

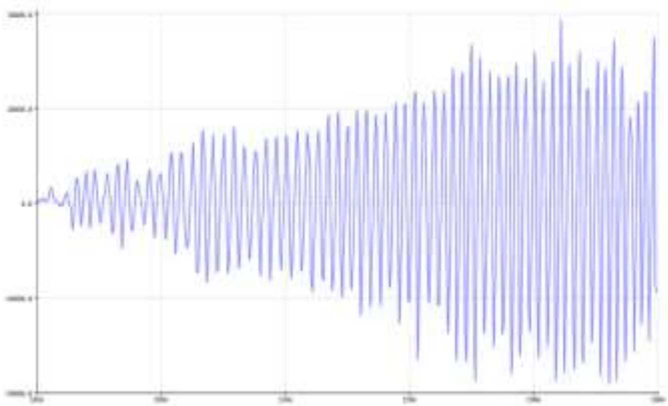

Figure 9. Test subject no. 1 seismograph results–Conventional foundationed high-rise structure model.

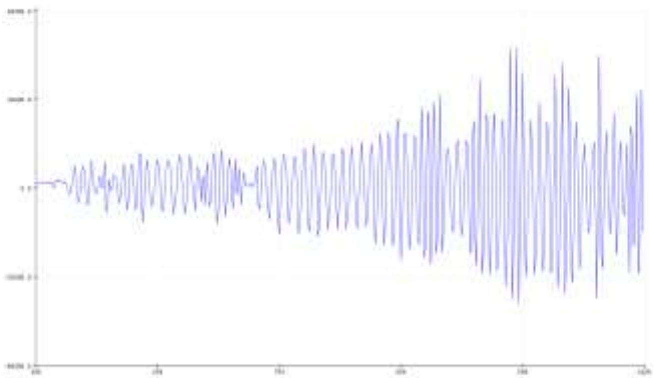

Figure 10. Test subject no. 2 seismograph results–base-isolated foundation high-rise structure model.

Table 1. Titan earthquake shake table –seismograph test result comparison.

Experiment	*Structure Model*	*Duration*	*Average Acceleration* ($\boldsymbol{m/s^2}$)
1	Conventional built foundation	90 seconds	1.1 m/s^2
2	Base isolation-equipped foundation	90 seconds	0.68 m/s^2

4. CONCLUSIONS

The effectiveness of the Titan earthquake shake table in capturing the performance of its test subjects were shown in terms of structural excitation through the produced seismographs from the Titan accelerometer sensors attached to the structural models. Overall, the study showcased the potential technological boosts of earthquake technologies to our structures through the use of a proper earthquake testing apparatus. In this case, it has been shown that the earthquake technology-equipped base isolation structural model has demonstrated major improvements in terms of structural resiliency during ground movements relative to the conventional foundation model as evidenced by the reduced or smaller value of acceleration of the former compared to the corresponding acceleration of the latter.

5. RECOMMENDATIONS

It is recommended that further improvements on the technological aspects of the research are necessary to provide more accurate real-time results. Moreover, a provision for a more user-friendly interface is needed so that undergraduate researchers can fully appreciate the technological advantages of using the earthquake shake table for their academic and laboratory necessities.

6. ACKNOWLEDGMENT

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