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Establishment of strong motion instrumentation program and shake table test on reinforced concrete bridge column

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Abstract

The Earthquake Engineering Center (EEC), NWFP University of Engineering and Technology, Peshawar, is working on the establishment of Strong Motion Instrumentation Program (PkSMIP). The project is being sponsored by the Higher Education Commission (HEC) of Pakistan with an estimated cost of Rs. 35 million. In this project strong motion sensors will be installed on ground, bridges and buildings across various regions to record ground motion and response of structures during earthquakes. The recorded ground motion and the response of the structure will be shared with researchers in earth sciences and structural engineering, for updating the seismic codes for bridges and buildings of Pakistan. This paper presents various aspects for successful installation, maintenance and data recording by sensors for which California Geological Survey (CGS) also provided technical assistance. Various aspects are discussed, such as, optimal cost, selection of site, security, maintenance, identification of installation points on structure as well in free field. The first author as part of his PhD studies gathered field data of bridges in northern part of NWFP and Kashmir and conducted the first shake table test on bridge columns. Various important aspects for conducting shake table tests on scaled models are presented. The tests conducted showed that valuable information regarding seismic performance of structures can be obtained through shake table tests, which can be used for improving seismic performance of such structures and for updating seismic design codes to ensure safer designs.

1. Introduction

The October 8, 2005 earthquake of moment magnitude (M_w) 7.6 (United States Geological Survey, 2005) clearly demonstrated that for public safety and continued economic growth of country, it is necessary to mitigate structural damages resulting from earthquakes. In this regard it is vital to have a seismic design code that addresses issues that are central to earthquake-resistant design. In 1967, the Government of Pakistan came up with the Code of Practice for Highway Bridges (CPHB, 1967): the document is outdated and no updates have made to it. Updating of structure design codes is a continuous process, with codes evolving as our understanding of behavior of structures improves. The codes evolve from research conducted on seismic hazard, structural behavior, performance of materials, and rigorous testing of structures in field and laboratories. On the basis of research outcome revised seismic hazard maps, locations of faults and safety margins related to structural parameters are updated in codes for reliable performance of structures.

Structural systems can be quite complex and usually exhibit non-linear behavior, particularly during extreme events such as earthquakes of large magnitudes. The highly non-linear behavior occurs due to cracking of materials such as concrete and yielding of reinforcing steel. The performance of structures during seismic event is closely associated with location of the structures from the fault rupture, the directivity effect associated with direction of fault rupture, geo-technical setting, material characteristics, structural form, quality of construction and the codes used for design. It is a fact that frequency of large magnitude earthquakes (M_w 6 and higher) is less and data related to dynamic response of structures during such shaking is even rare (United States Geological Survey, 2009). Better understanding of seismic performance of structures is achieved through study of recorded response of structures during seismic excitation and testing in seismic research laboratories, which is typically done on reduced scale models. Various non-destructive field tests on prototype structures, either for seismic performance study or structural performance study under non-seismic loads is possible (Syed et al., 2007), which are done under controlled conditions. When earthquake occur, the loadings are extreme and study of structural response under such events provides invaluable information. With advent of affordable electronics and communication networks it is now becoming easier to instrument structures in field to record response of structures during earthquakes. For this reason sensors need to be installed on existing structures; these sensors need to be kept operational on continuous basis for years due to infrequent occurrence of large magnitude earthquakes.

Realizing the importance of strong motion instrumentation of structures, EEC in its currently underway capacity building project has undertaken "Pakistan Strong Motion Instrumentation Program" (PkSMIP). Under this program, strong motion sensors would be installed on ground and structures of various classes spread over different areas, with the aim of capturing response of these structures when subjected to strong motion earthquakes.

Important issues, such as, selection of structures, location of sensor installation, selection of structures within a class of structural system, geographical distribution of structures, optimization of sensor quantity, selection of suitable location for recorder, instrumentation security issues, routine maintenance, data collection and dissemination etc. are addressed in this paper. These issues were discussed with CGS team and technical assistance for establishment of PkSMIP was provided by the CGS team: the CGS team also assured of its support in future for managing and maintaining PkSMIP (Syed and Shakal, 2007).

In the later part of this paper information is provided regarding seismic test on scaled down model of Reinforced Concrete (RC) bridge column conducted in November 2006 on seismic simulator (shake table) in EEC. The test column was subjected to ground motion recorded at Abbottabad during the October 8, 2005 earthquake. It is believed that the test conducted is the first ever seismic shake table test on a bridge component in Pakistan.

2. Objectives of PkSMIP and shake table testing

Under the PkSMIP, strong motion sensors utilizing state-of-the-art technology would be installed on actual prototype structures. EEC intends to instrument 12 structures of various classes by utilizing minimum number of strong motion sensors for recording their seismic response during a seismic event. Sensors would also be installed on ground to record the input ground motion that excited the structure. The data thus gathered would be utilized in research. The recorded ground motion data would be used for computer based analysis of structures and for using as input excitation for shake table tests of structures. Such research would help in improving our understanding of complex nonlinear behavior of structures under earthquake loadings and contribute towards development of seismic design codes for local conditions.

3. Selection of structures

The physical infrastructure comprises of many types of structures, ranging from residential and commercial buildings, highway bridges, communication and electricity towers, tunnels, dams, industrial installations and power plants etc. Within a structural system, there exist various structural forms; for example, within residential buildings there are stone masonry, brick masonry RC buildings. In bridges, the key component that resists the lateral forces of earthquake are piers, which are vertical components starting from ground and reaching the roadway part above. The piers can be in the form of columns, and within each type of bridge system there can be single-column pier and multiple-column piers. The bridge piers can be further classified based on their geometric configuration, such as, circular, square, rectangular and other shapes. Thus a huge variety of structures and their subclasses exist with further breakdown with respect to other details as discussed above. The structural form or configuration of a structure plays a vital role in enabling a structure to withstand and survive earthquake induced forces that act upon it. The distance of structure from earthquake epicenter and type of soil upon which it is built are some of the other factors upon which the seismic performance of a structure depends.

In the initial phase of PkSMIP, EEC intends to focus on structures that are considered to be a vital part of the physical infrastructure and comprise a significant portion of the physical infrastructure. Therefore, in the initial phase of PkSMIP, important buildings and bridges in high seismic risk area would be fitted with instrumentation for recording their response in future earthquakes.

The authors had meetings in Peshawar to decide distribution of sensors for various structures. It was decided to initially instrument eight (8) buildings and four (4) bridges in the earthquake affected and adjoining areas. In order to capture the behavior of different structural forms in buildings, it was planned to instrument buildings made of confined and un-confined brick masonry, RC frame buildings and one steel frame building. In case of bridges, it was decided to instrument one (1) tall single-column bridge pier, as these are quite common in bridges. It was further decided that selection of remaining three (3) bridges for instrumentation would be made on the basis of their importance and the consideration whether they are located in a zone of relatively high seismic risk.

3.1. Other considerations for selection of structures

Under PkSMIP, those bridges, for which structural drawings are available, would be considered as good potential candidates for installation of sensors. This is very important because after the occurrence of an earthquake the recorded response would need to be studied and compared with responses predicted by numerical analyses, for which structural drawings are required. Among buildings, properly engineered buildings would be considered for instrumentation, however semi-engineered and non-engineered buildings will also be considered as these form significant portion of building stock. For selected buildings, if drawings are not available, a thorough study would be conducted to document complete structural details. This would facilitate comparison of actual building response and response computed from numerical analyses.

3.2. Potential candidate structures

The first two authors of this paper jointly visited various areas of Pakistan in March 2007 (State of California, 2007; Syed and Shakal, 2007). These areas included Muzaffarabad, Garhi Habibullah, Balakot, Mansehra, Abbottabad, Havalian, Khairabad at the crossing of Grand Trunk (GT) Road and River Indus, Peshawar and Islamabad. One objective of the visit was to study the structures and make list of potential candidate structures based on the theme discussed in preceding paragraphs. Some of the potential candidate structures are shown in Fig. 1 through Fig. 5.

Fig. 1. Administration Block, NWFP University of Engineering and Technology, Peshawar (a new 4-story RC frame building).

Fig. 2. Ayub Medical Complex (AMC) Hospital Abbottabad (3-story RC frame structure).

Fig. 3. Main University Building, CMH Road, Muzaffarabad (2-story steel frame structure constructed after the earthquake).

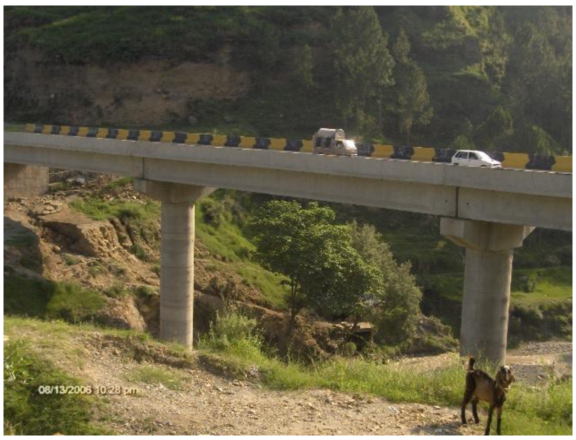

Fig. 4. Three-span RC Bridge near Mansehra (Mansehra-Balakot Road).

Fig. 5. Continuous RC box girder, New Khairabad Bridge, on River Indus GT Road (N5).

A conscious effort was made to select structures in different geographic locations and in areas of high seismicity such as Zone 2B, Zone 3 and Zone 4 (BCP, 2007). The greater spatial spread of structures increases the likelihood of capturing response of ground shaking in future earthquakes.

4. Sensor selection, installation and optimization

At the time of project inception in early 2006 it was decided to procure twelve (12) Data Acquisition Systems (DAQs) with capacity to connect 12 sensors. It was planned to procure 36 tri-axial accelerometers and 36 uniaxial accelerometers, making a total of 144 sensors for the entire project. However, after interaction with team of California Strong Motion instrumentation Program (CSMIP) of California Geological Survey (CGS), it emerged that uniaxial accelerometers are more beneficial than tri-axial accelerometers. This is due to the reason that not all the points of installation on a structure require capturing response in all the three directions. Thus uniaxial accelerometers would give flexibility to install sensors only in direction that is of interest and thus avoid using sensors that may be redundant if tri-axial sensor is used. During the visit it was concluded that for twelve structures, only twelve (12) tri-axial accelerometers would be acquired for free field ground motion recording and the rest of the 108 sensors could be uniaxial sensors.

An important aspect of PkSMIP sensor installation would be comprehensive documentation. The documentation is planned to have structural drawings marked with sensor showing its serial number, direction of sensor orientation etc. Every structure is planned to have a separate folder at EEC having structural drawing, structural modeling in Finite Element Analysis/Method (FEA or FEM) and its results, deployment plan of each sensor, maintenance log, report of any repairs, name of all persons involved in installation and maintenance, pictures of sensor installed etc. Another aspect to be assured at first installation or after removal of sensor for maintenance is sequence testing. Sequence testing is a procedure in which it is tested that sensor is connected to correct channel on the DAQ system. This means if a sensor is connected to wrong channel then the recorded response would be of other location or direction whereas it would be reported to be of another location and direction for that channel. Thus sequence testing is important aspect for acquiring correct data for respective direction and location.

Now very briefly the selection of installation points and optimization of sensors quantity is discussed for the bridge shown in Fig. 4. It is a two lane, 3-span Highway Bridge constructed probably in year 2004. The bridge has experienced the October 8, 2005 M_w7.6 earthquake and is approximately 40-45 kilometers from the earthquake epicenter. The Bridge has two circular piers approximately 18 meter in height. The first two authors during their visit to the bridge site discussed and recommended installation of one free field tri-axial accelerometer at abutment level away from structure, as acceleration amplification is expected at this level compared to the river bed, and it is important to know the input ground motion for the abutment. It was further recommended to install two uniaxial sensors at base of one pier for recording the two horizontal components (longitudinal and transverse) input motion imparted to the pier; two uniaxial sensors at transom top for longitudinal and transverse response; two uniaxial sensors at the center girder at mid height; two uniaxial sensors at underside of deck slab above the transom for recording deck response in longitudinal and transverse direction; and one uniaxial sensor for longitudinal response of abutment top. The proposed locations of the sensors to be installed are shown in Fig. 6 through Fig. 8. It can be seen that only one span out of three are instrumented to capture the response, this technique is quite useful as it is cost effective and greater number of structures can be instrumented using this optimal approach.

5. Security and maintenance issues

For keeping the installed sensors and its allied facilities in proper working condition for years, requires consideration of safe installation, maintenance and recovery after a major event. Trained staff is essential for maintaining such sophisticated equipment. NWFP University of Engineering and Technology (NWFP UET) has a dedicated Scientific Instrumentation Center (SIC) with capable staff, which is responsible for maintenance of instruments at NWFP UET. This staff would be further trained to help in carrying out routine maintenance for successful running of PkSMIP (Syed and Shakal, 2007).

To avoid vandalism preference would be given to install the sensors, cable conduits and DAQ at locations that attracts least attention of people and is difficult to access under ordinary circumstances, however, due attention is required that easy access to technicians is possible. Sensors installed in bridges near the ground are vulnerable to water submersion in floods, therefore, special arrangements would be made to prevent water coming into contact with such sensors.

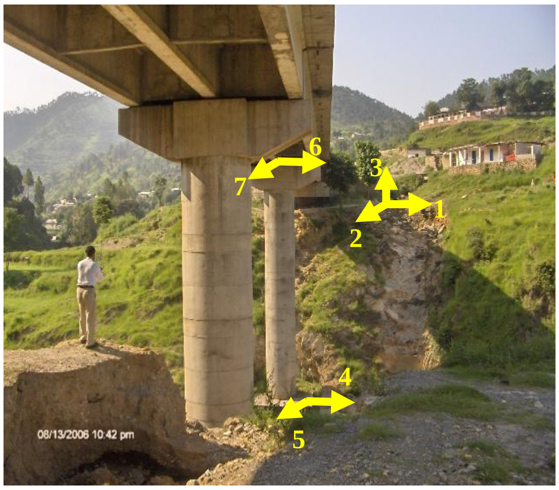

Fig. 6. Location of 7 sensors (3 free-field, 2 at pier base and 2 at pier top).

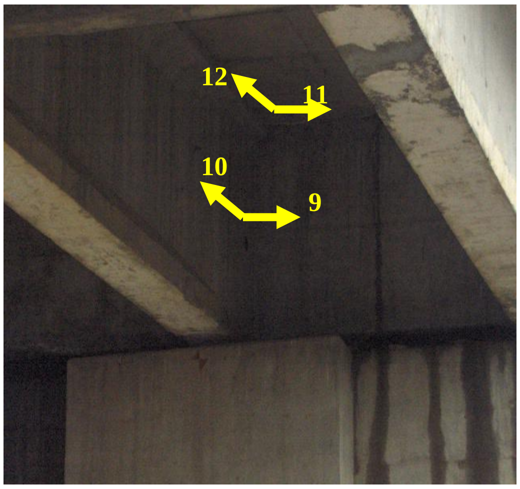

Fig. 7. Location of 4 sensors (2 at girder mid height and 2 at deck).

Fig. 8. Location of 1 sensor at abutment.

In order to minimize maintenance and data recovery costs, the sensors should be able to carry out self-diagnostics and send data remotely via telemetry to EEC, Peshawar. Diagnostic checks can be run manually or automatically performed after certain fixed intervals in routine or after an event. Maintenance staff would be dispatched only when a sensor fails to respond.

6. Data collection and dissemination

The data collected from sensors network would be invaluable. In order to assess the data and to draw meaningful conclusions from it, various exercises ranging from very simple calculations to complex may be done to investigate the response and behavior of instrumented structures. Finite Element Analyses (FEA) of instrumented structures may need to be carried out for thorough understanding of instrumented structures. Usually this exercise requires huge effort to process the data, conduct dynamic analyses of the structure and drawing meaningful conclusions. This would be taken up in research projects at postgraduate level or in faculty conducted research projects. The data and results from such studies will be shared with researchers across the world. Such results and conclusions would help in updating the seismic design codes.

7. Shake table test on RC bridge column

As part of the Ph.D. research of the first author, data with regard to bridges in northern part of NWFP and Kashmir was collected by extensive field visits (Syed et al., 2006; Syed and Shakal, 2007; EERI, 2006; Naeem et al., 2005). The location of some of the surveyed bridges can be seen in a Google® Map (Syed, 2008). During the site surveys, data was collected pertaining to the geometry and configuration of bridges, GPS coordinates of bridge site, and the quality and consistency of concrete used in construction. The quality of concrete was assessed by estimating the concrete strength by using Schmidt Hammer (Malhotra and Carino, 2003). Schmidt Hammer is an instrument for estimating in-situ strength of concrete by non-destructive technique. The hammer measures the rebound of a spring loaded mass impacting against the surface of the concrete to be tested. The impacting mass carries a defined energy. Its rebound is recorded and the concrete strength estimated by correlating the rebound number/value to the concrete compressive strength. Majority of the bridges exhibited rebound values in range of 25-35 (12.4-16.5 Mega Pascal (MPa)), concrete in few bridges gave high rebound values in 60's 60, however, concrete in some bridges gave quite low rebound values in 10's. In bridges with low rebound values, significant variation was seen throughout the substructure, which indicates poor quality control during construction. In bridges with high values of rebound number, the quality of concrete seemed to be uniform throughout the substructure. From the survey data it was decided to fabricate bridge columns with concrete cylinder strength (ASTM C873-04, 2004) of 16.5 MPa.

After the field surveys, scaled bridge model of RC single column solid bridge pier was fabricated for testing on the shake table. The scaled model is shown mounted on the shake table in Fig. 9. The objective of the test was to study the behavior of RC bridge piers of this class. A scaling factor of 10 was selected to reduce the dimensions of the model in order to facilitate fabrication and testing on the shake table. Preparation of a true (complete) model was not possible due to inability to scale down mechanical properties of reinforcing steel, thus simple model was used (Harris and Sabnis, 1999). Various parameters for the prototype and model RC bridge column are presented below in Table 1.

Table 1. Parameters of prototype and model RC bridge column.

Parameter	Prototype	Model
Scale Factor	1	10
Column height	7.6 meter	0.76 meter
Diameter	1 meter	0.1 meter
Dead load	100 ton	1 ton
Concrete cylinder strength	16.5 MPa	16.5 MPa
Yield strength of steel	413.7 MPa	413.7 MPa
Diameter of steel	25 millimeters	9.5 millimeters
PGA	0.23 g	2.3 g
Earthquake duration	50 sec	16 sec
Column base	-	1 ton
Total weight	-	2.1 tons

Fig. 9. 1st shake table test of RC bridge pier conducted in November 2006.

Since seismic simulator testing is a dynamic process in which events take place in split second, therefore, great care in various aspects is required. The test models have to be of size and weight which is within the limits of shake table capacity. The specification of the shake table is provided in Table 2. The first issue was mounting the model on the table top; if the model is not properly anchored to the table top, various complications can occur, such as, rocking, slippage etc., which can significantly modify the true response of the model. Slippages and rocking at the model base can modify the shake table control and it becomes difficult to achieve the desired table motion. An important change in structural response can be seen in the form of increase in damping ratio which is not desirable. Slippage at connection can break the connection and the test specimen can fail and fall on the table which can damage the equipment. Therefore, special attention to anchoring was given and 12 bolts, each having 12 millimeters diameter was used to connect the test model base to shake table top.

Once the model is anchored to base, next step was to carry out the "Equalization Process", in which the model is imparted small accelerations and its response is recorded. From the recorded data, a transfer function is developed for the shake table that would move the shake table in such a manner that its movement nearly exactly simulates the earthquake time history record to which the model is to be subjected to. The process of equalization is model specific, as mass and stiffness of the model affect the transfer function. This process is very sensitive and extreme care is required during this process by keeping tight control over threshold parameters such as table displacement, velocity and acceleration. In the event of overshooting of the table, which is not unlikely, the model can get prematurely damaged, resulting in loss of the model and loss of opportunity to collect test data. During testing, it was ensured that equalization process was completed by starting with small intensity shaking. Special attention was given to shake table control such that ambient conditions, such as, temperature and pressure of hydraulic oil driving the shake table, remained within permissible limits.

Table 2. Specifications of the shake table.

Parameter	Value
Shake Table Model	R-141
Make	ANCO USA
Size of table top	1.5 meter x 1.5 meter
Maximum acceleration at 4000 kg*	±1.1g
Maximum velocity at 4000 kg*	±1.1 meter/sec
Maximum displacement	±125 millimeters
Maximum safe payload	8000 kg*
Frequency range	0-50 Hertz
Overturning moment	10 ton-meter

* "kg" stands for kilogram

The model bridge pier was subjected to October 8, 2005 time history recorded at Abbottabad. The model was subjected to gradually increasing acceleration intensity. This was done by starting from 5% scaled ground motion to 100% of the scaled time history and the corresponding response of the model was recorded. Three accelerometers were installed on the test column to measure longitudinal motion. The first accelerometer was installed on table top to measure the input motion from table; second accelerometer was installed on the column base to measure base motion to verify that no slippage occurred between the column base and the table top; and the third accelerometer was installed on the column top to measure the response of column as a result of shaking. The response amplification of around 1.3 was observed at the column top when subjected to 100% of scaled time history that corresponded to Peak Ground Acceleration (PGA) of 2.3 g, where g is acceleration due to gravity. The column was severely damaged but did not suffer total collapse. Important lessons were learnt from this first shake table test which showed that properly constructed structures can withstand strong earthquake motions without collapse and prevent loss of functionality and life. The test also showed that since bridges are heavier than buildings, therefore, large shake tables are needed with bigger payload capacity if relatively larger sized models are to be tested. Smaller models, employing higher scale factor can be used to bring the model size to within the payload capacity of the shake table at EEC, however, with higher scaling factor, the correspondence between the model and the prototype is affected to some extent. This has the undesirable affect of reducing the correspondence between the model and the actual prototype structure.

8. Conclusions and Recommendations

1. Parts of Pakistan are under high seismic risk. Mitigation of risks posed to the infrastructure due to high magnitude earthquakes, requires better understanding of intensity of earth shaking that can be expected in an earthquake, the attenuation characteristics associated with an earthquake in a particular area and the ability of the infrastructure to withstand the earthquake loading imposed on it. Establishment of Pakistan Strong Motion Instrumentation Program is a necessary step that would provide data for improving understanding of these issues. The acceleration vs. time (time-history) data recorded by installed instruments can be shared with researchers involved in earth sciences and structural engineers for updating the seismic design codes for structures.
2. In the initial phase of PkSMIP, selected bridges and buildings in the area affected by the earthquake of October 2005 and high seismic risk areas would be fitted with instrumentation for recording time-history data under future earthquakes. Initially, eight (8) buildings and four (4) bridges would be fitted with instrumentation. Initially, twelve (12) Data Acquisition Systems, 12 tri-axial accelerometers and 108 uniaxial accelerometers would be installed on various structures, making a total of 144 sensors for the entire Program. It is believed that this level of instrumentation would suffice in the initial phase of the program, and would provide acceptable spatial coverage in terms of area covered, and would also cover most common types of structures such as bridges and buildings.
3. Establishment of Pakistan Strong Motion Instrumentation Program would serve the following useful purposes;
   i. It would provide useful information on the shaking experienced by structures, such as, bridges and buildings when subjected to strong earthquakes;
   ii. It would provide useful information about the actual behavior of the structures and their components during an earthquake.
   iii. Data collected under the PkSMIP would be most useful for updating and improving the seismic design codes.
4. Keeping the instruments installed under the PkSMIP operational on long-term basis is a challenging task that would require careful planning rigorous operation and maintenance procedures.
5. Shake table testing of model structures is an important activity for improving existing construction practices and existing structure design codes that can complement information collected under PkSMIP.

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