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SEISMIC HAZARD ASSESSMENT FOR PHASE-I DESIGN, HAKKARI DAM, TURKEY

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SUMMARY

Deterministic and probabilistic seismic hazard analyses are used to select ground motions at the Hakkari dam site, Turkey. Deterministic analysis indicates that an M_w 7.4 14 km from the dam is the Controlling Maximum Credible Earthquake (CMCE). The CMCE has an estimated PGA of 0.34g (median) and 0.50g (84th-percentile) for critical dam structures.

Probabilistic analysis used 11 source zones, a background seismic activity rate and three equally-weighted PGA attenuation relationships. The 475-year return period PGA of 0.26g is recommended as the maximum design earthquake for non-critical structures. A PGA of 0.17g is recommended for the operating base earthquake ground motion.

INTRODUCTION

The Hakkari Electric Power Project (HEPP)—one of nine planned developments under a U.S.-Turkish Joint Statement for bilateral cooperation—has completed Phase I final design. The Hakkari Consortium of U.S., Turkish and Swiss companies will complete design and construction of HEPP. The owner and operator of the HEPP will be the Turkish State Hydraulic Works—Devlet Su Isleri (DSI). Elektrik Isleri Etut Idaresi (EIE) provided an initial HEPP conceptual design and layout comprising a rock-fill embankment dam, 11-km long power tunnel and an annual generation capacity of 625.5 GWh. Pietz and Aker [1] summarized the main features of the project.

The HEPP is located in Southeastern Anatolia, within the rugged and mountainous Zap River basin between 37.23° and 38.39°N and 43.30° and 44.56°E (Figure 1). The project catchment area of 4763 km^2 includes elevations ranging from 1200 to 4100 meters above sea level (m.a.s.l.). The Zap River and its tributaries are deeply incised to form narrow, steep-sided valleys. The Hakkari dam is proposed as a zoned embankment with a central clay core and rockfill shells. The crest elevation of the dam will be

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1445 m.a.s.l. The dam will have a total structural height of 220 m, crest width of 12 m and crest length of approximately 525 m.

The Hakkari Consortium recognized that a regionally high earthquake hazard could impact dam design. They indicated that investigations of nearby faults and regional seismicity were needed to establish a design earthquake and associated ground motions. This paper:

- Describes the nature and results of investigations to establish the location and magnitude of strong earthquake shaking at the HEPP; and
- Presents preliminary earthquake ground motions proposed by the Hakkari Consortium for Phase-I final design.

Our earthquake hazard investigations and analysis demonstrate how local geology and historical seismicity are used to set seismic design parameters. We use both deterministic and probabilistic methods to quantify earthquake ground shaking for the HEPP.

SEISMOTECTONIC SETTING OF THE HAKKARI PROJECT

The Hakkari region lies near the southern end of a 1000-km wide zone of active crustal deformation that extends from the Greater Caucasus in the north to northern Iraq in the south (Figure 1). The deformation accommodates relative motions between the African, Arabian and Eurasian tectonic plates.

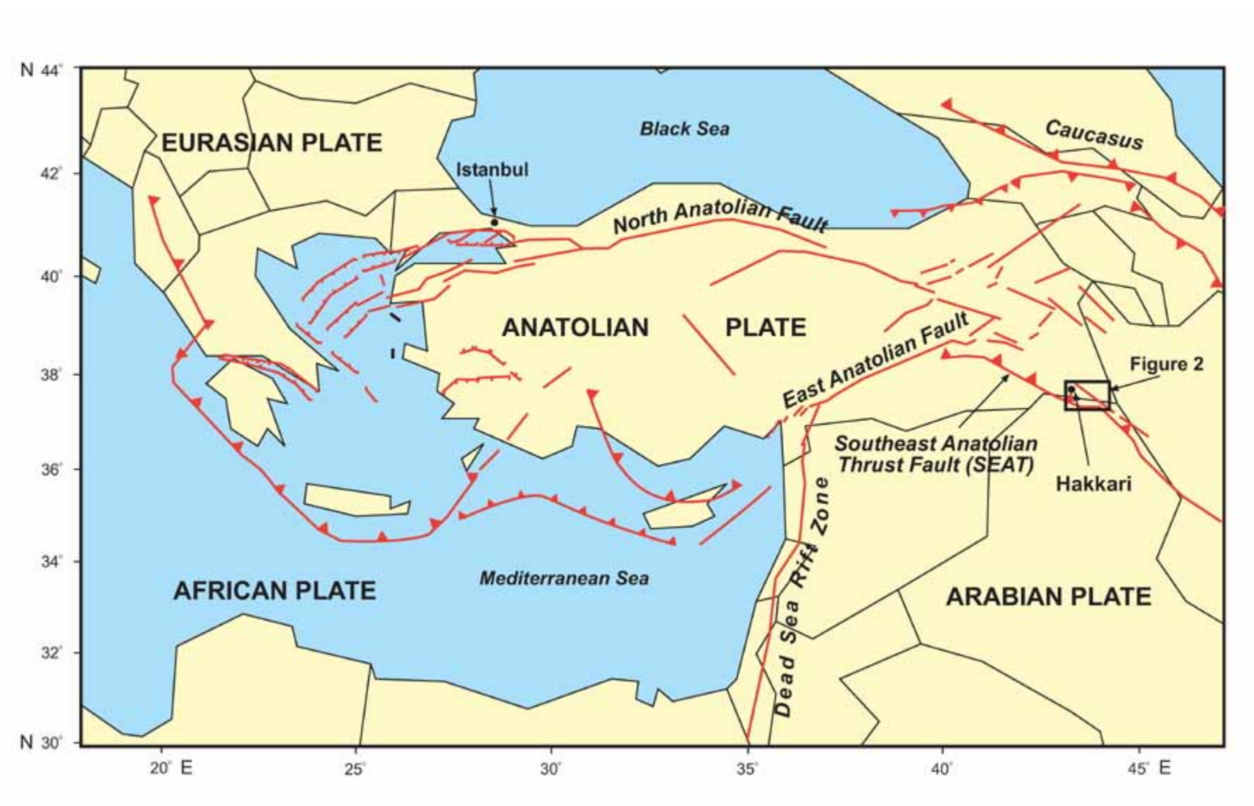

Figure 1: Map of eastern Mediterranean showing major geological structures and faults at the convergence of the African, Arabian and Eurasian tectonic plates. Solid lines are strike-slip faults, ticked lines are normal (extensional) faults, and barbed lines are thrust (contractional) faults. Solid black lines are international boundaries.

Global plate tectonic models predict that over the last three million years the northern Arabian plate has moved northwestwards (N23 ± 7°W) at an average velocity of 24±2 mm/year relative to the Eurasian plate. As the plates have collided, both reverse and strike-slip faults have formed. Movement along these faults has caused the uplift of mountains, and the westward translation and rotation of much of central and western Turkey (e. g. Jackson and McKenzie, [2]). GPS results show that plate motion vectors are similar to the north and south of the Southeast Anatolian Thrust fault (SEAT) west of Lake Van (Figure 1).

The present-day complex tectonic and geological setting of the HEPP comprises the following major features:

- Crustal strain is distributed across a zone about 1000 km wide between northern Iraq (Arabian Plate) and Greater Caucasus (Eurasian plate), rather than being accommodated on any single large geological structure;
- Strain is partitioned between structures that move in a predominately strike-slip sense (lateral motion) and those that move in a predominately reverse sense (shortening motion);
- Crustal shortening is accommodated principally by movement at east-west striking thrust and reverse faults in the Caucasus; and
- Lateral movements are accommodated principally by motion along northwest-striking, right-lateral faults in eastern Turkey and northwestern Iran.

Historical Seismicity

Hakkari is in a region of historically moderate macroseismicity (earthquakes of $M \geq 4$) based on an incomplete record extending back 1,500 years (Table 1). The U.S. Geological Survey PDE catalog contains 224 records of earthquake hypocenters within about 200 km of Hakkari since 1973. All but one of these earthquakes has magnitudes less than m_b 5.8. Only 10 of these earthquakes have been located within 50 km of Hakkari (Table 1). Earthquakes in 1990, 2000 and 2002 (28 February) were reported as felt locally. The largest was a m_b 4.7 in February 2002. Its epicenter was located approximately 48 km from the HEPP site.

Major Faults Close to the Project Site

Studies of large historical earthquakes from many regions of the world show that they are often associated with surface displacements along active faults. The amount of movement along a fault typically ranges from less than 1 m to more than 10 m. Surface fault rupture lengths range from a few kilometers to nearly 300 km, and are associated with earthquakes from about M 6 to M 8.5. The 1992 Active Fault Map of Turkey of Saroğlu et al. [3] shows the SEAT and the Semdinli-Yuksekova fault zone within 50 km of the HEPP site. We investigated these faults to determine their potential to generate strong ground motions at HEPP.

Southeast Anatolian Thrust Fault (SEAT)

The SEAT is exposed about 1 km downstream of the proposed Hakkari dam (Figure 2). Its trace cuts the proposed power tunnel alignment. The fault locally places younger schist of the Urse formation over older karstic limestone and dolomite of the Midyat Formation.

The close proximity of the SEAT to Hakkari dam makes understanding its earthquake potential critical for seismic design at HEPP. The only known historical surface rupture near the SEAT occurred about 300 km northwest of HEPP in 1975. Taymaz et al. [4] report about 20 km of surface fault rupture with a maximum vertical displacement of about 0.6 m associated with the M 6.7 earthquake.

Table 1: Selected Historical and Instrumental Earthquakes near HEPP

Date (dd-mm-yyyy)	Latitude (ºN)	Longitude (ºE)	Magnitude	Distance from HEPP (km)
?-?-628	35.5	44.4		
25-07-1135	36.1	45.9	6.1	
13-08-1135	36.1	45.9	6.4	
29-04-1179	36.5	44.1	6.6	
18-11-1226	35.3	46.0	6.5	
?-?-1310	35.6	46.1	>5.3	
?-?-1503	37.4	43.8	6.9	Felt at Hakkari city
22-09-1666	37	43		Felt at Hakkari city
?-?-1714	36.2	44.0		
?-?-1802	35.6	45.4		
?-06-1837	38.7	44.8		
17-03-1871	38	43	6.8	Felt at Hakkari city
18-02-1974	37.57	43.43	4.0	24
10-03-1983	37.23	43.67	4.6	37
11-04-1990	37.80	43.74		25
12-12-1996	37.87	43.42	3.2	41
07-08-1998	37.73	43.45	4.6	28
25-10-2000	37.69	43.37	3.9	32
12-08-2001	37.22	44.03	4.3	47
02-12-2001	37.44	44.19	4.3	43
28-02-2002	37.28	44.14	4.7	49
01-04-2002	37.14	43.85	4.2	48

Notes:

1. Historical magnitudes are surface wave (M_s); instrumental magnitudes are body-wave (m_b) magnitude.
2. Instrumental locations and magnitudes from the USGS/NEIC PDE (1973-present) catalog.
3. Distance from Hakkari based on a dam site location at 37.57ºN, 43.71ºE.
4. Hakkari city has a present population >50,000 and is about 17 km southwest of the Hakkari dam site.

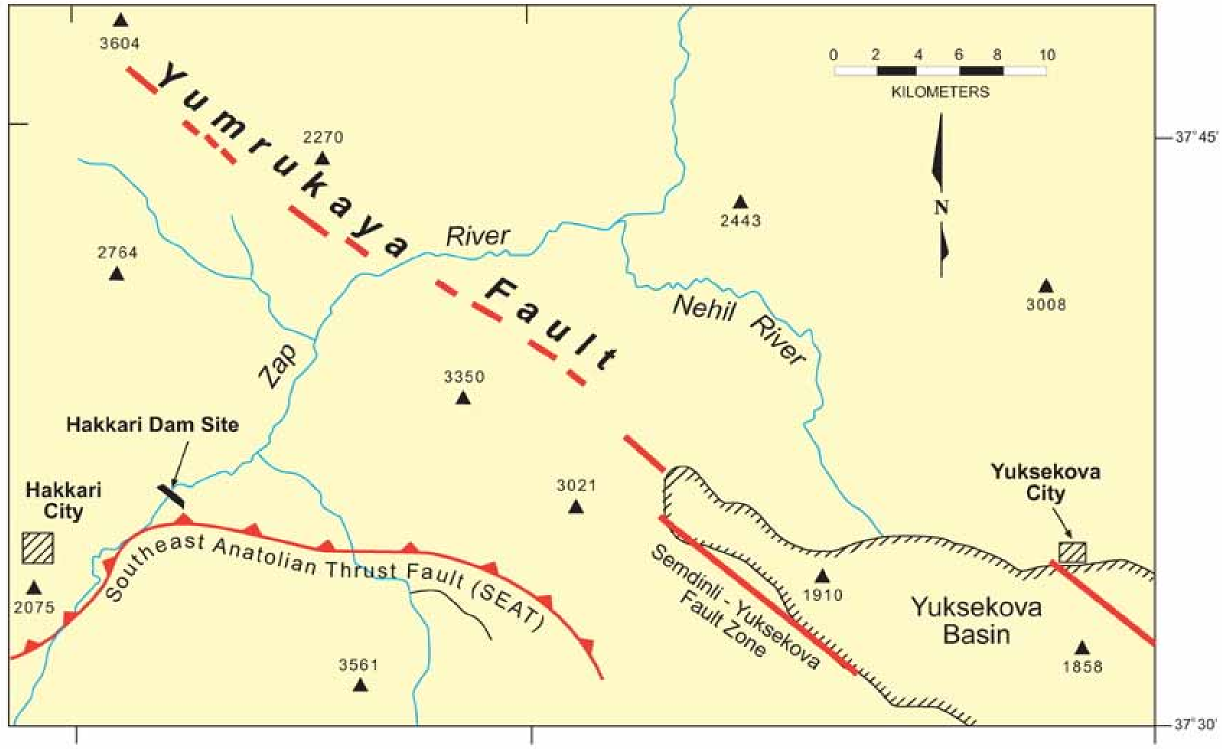

Figure 2: Map of Hakkari region showing major faults, topographic features and newly-discovered traces of the Yumrukaya fault.

We investigated the past activity of the SEAT near Hakkari by excavating a trench across an alluvial terrace where the SEAT trace crosses the Zap River. Loose, well-bedded alluvial gravel and sand exposed in the trench showed no evidence of disruption by faulting. No non-sedimentary preferential alignment of gravel clasts that may indicate faulting was observed. The age of the alluvial terrace is unknown.

Two terrace remnants are preserved about 300-400 m above the Zap River about 4 km downstream of the Hakkari dam site. They show an elevation difference of about 80 m across the SEAT—the lower terrace is cut in limestone on the footwall of the SEAT. Both terrace surfaces are underlain by calcite-cemented alluvial gravel and sand. The terraces show no clear markers to confirm that they are the same age. Their elevation difference across the fault could be the result of different-aged surfaces preserved at progressively lower river levels. Alternatively, they could be the same terrace that has been offset by about 80 m across the SEAT. The age of the terrace(s) is unknown but they are probably less than 1.6 million years old (Pleistocene).

Trench data provide positive evidence that the SEAT has not had very recent surface displacement near Hakkari. Differences in elevation of higher, older terraces probably represent different former river levels rather than a large vertical fault separation. Large-scale, regional and local data all suggest that the SEAT is no longer active. Without positive evidence for recent surface fault movement, we assume the SEAT is not a significant source of future large earthquakes at HEPP.

Semdinli-Yuksekova Fault Zone
Saroğlu et al. [3] also show traces of the Semdinli-Yuksekova fault as a zone of probable active faults east of Hakkari city (Figure 2). No traces are shown within about 50 km of the HEPP. However, our aerial photograph analysis and field investigations show clear evidence of surface faulting within 15 km of the Hakkari dam site. Interpretations from field and aerial photograph studies reveal:

- A minimum of 29 km of discontinuous 1-2 km long, fault traces to the northwest and southeast of the Zap River (Figure 2);
- 15 km of continuous fault trace that offsets horizontally and vertically the topography at the northwestern end of the Yuksekova basin;
- Truncation and apparent right-lateral offset of a small, glacially-formed ridge (arête) along the fault trace (Figure 3);
- Abrupt changes in rock type across narrow zones of crushed and sheared rock;
- A shear zone that dips steeply (55°-75°) north-northeast near Yumrukaya ruins (Yumrukaya fault), about 14 km northeast of the proposed Hakkari dam site. The shear zone crosscuts the topography and moderately south-dipping (25°) rocks of the Urse Formation;
- A 100-150 m wide zone of hydrothermal alteration and deposition, including active springs along the Yumrukaya fault;

The Yumrukaya fault appears to be part a northwest extension of the Semdinli-Yuksekova fault zone. We have not yet determined the date of the last surface fault movement along the Yumrukaya fault. However, well-developed topographic lineations along the Yumrukaya fault and other fault traces within the Semdinli-Yuksekova fault zone provide sufficient evidence that these faults are active (moved at least once in the last 10,000-15,000 years). We conclude, therefore, that the northwest-striking Yumrukaya fault is the closest large earthquake source to the HEPP.

DESIGN EARTHQUAKE GROUND MOTIONS

Geological and geophysical studies provide information on the sources and frequency of earthquake shaking at the HEPP site. This hazard information needs to be translated into recommendations for engineering design. We chose to follow the guidelines of the International Committee on Large Dams (ICOLD, [5]) because they are widely recognized and accepted. The guidelines require both deterministic and probabilistic seismic hazard analyses for different elements of the HEPP.

Deterministic analysis

The deterministic approach uses available historical seismic and geological data to generate discrete, single-valued events or models of ground motion at the site. Typically, one or more earthquakes are specified by magnitude and location with respect to the site. In tectonically active areas like Southeastern Anatolia, earthquakes are assumed to occur at faults, and on the part of the fault closest to the site. Site ground motions are estimated for a specified earthquake magnitude, source-to-site distance, and site condition.

Figure 3: View northwest glacial ridge offset by horizontal movements along the Yumrukaya fault—a northwestern extension of the Semdinli-Yuksekova fault zone. The higher linear ridge in the center background has been offset to the right with respect to the lower ridge in the foreground. Two strong lineations on the lower ridge are probable fault traces. The gray zone comprises broken and sheared rocks within the fault zone (Photo R. Harlan).

Deterministic analysis uses a concept of maximum credible earthquake (MCE). The MCE is the largest reasonably conceivable earthquake that appears possible along a recognized fault or within a geographically defined tectonic province, under the presently known or presumed tectonic framework. Little regard is given to the probability of occurrence, which may vary from less than a hundred to more than ten thousand years, depending on the geologic environment considered. Since a project site may be affected by earthquakes generated by various sources, each with its own fault mechanism, maximum earthquake magnitude and distance from the site, multiple MCE's are defined for the site. Each MCE has its own characteristic ground motion parameters and spectral shape.

The controlling maximum credible earthquake (CMCE) is the most critical of all MCE's capable of affecting a dam. It is the MCE that would result in the most severe consequences for the dam. The CMCE is determined after successively assuming that each MCE would occur along its associated fault, or within its associated tectonic province, at a location closest to the dam.

Probabilistic analysis

Probabilistic analysis assesses the likelihood that ground motions will equal or exceed a specified value during a specified time. The probability or frequency of occurrence of different magnitude earthquakes on each significant seismic source and inherent uncertainties associated with the attenuation of ground motions are incorporated into the probabilistic analysis. The analysis is used to select the site ground motions based on the probability of exceedance of a given level of earthquake shaking during the service life of the structure or for a given return period.

Our probabilistic analysis for HEPP had the following features:

- Eleven seismic source zones based on major seismotectonic provinces covering a region from 34º-45ºN and 33º-52ºE;
- A background earthquake occurrence rate of one M 5.5/100 years and one M 6.5/1000 years for every 1° by 1° of area not included in a seismic source zone;
- 6624 earthquakes from 15 catalogs of historical earthquakes over about the last 2,000 years; and
- Three attenuation relationships developed from worldwide and California, USA strong motion records.

Median peak horizontal ground motions (PGA) were calculated for HEPP using the SEISRISK III seismic hazard program of Bender and Perkins [6]. Accepted PGA values were the average of PGAs calculated for rock sites (average shear-wave velocity about 760 m/sec) for both strike-slip and reverse earthquakes from each of the three attenuation relationships.

Maximum design earthquakes

The maximum design earthquake (MDE) is the maximum level of ground motion for which a structure is designed or evaluated. For Hakkari dam and other critical features whose failure could result in uncontrolled release of a reservoir, the ground shaking from the CMCE was selected as the MDE. For all other critical features whose failure would not result in uncontrolled release of the reservoir, we selected an MDE less than the CMCE. The consequent lesser ground motions for these critical structures permit economical designs that meet appropriate safety standards.

MDE for Hakkari dam and other critical structures

Our deterministic analysis showed that the Yumrukaya fault —14 km from the Hakkari dam site— is the CMCE. The magnitude of the CMCE was estimated with empirical relationships between earthquake magnitude, fault rupture length, rupture area and coseismic slip amount (e.g. Wells and Coppersmith, [7]; Hanks and Bakun, [8]). These relationships indicated a CMCE of M 6.8. However, four 20th Century historical earthquakes ranging in magnitude from M 6.6 to M 7.6 caused surface rupture along similar strike-slip faults in northwest Iran and eastern Turkey (Talebian and Jackson,[9]; Saroğlu et al., [3]). Three of these four earthquakes had magnitudes of $M_s \geq$ 7.4, but with relatively short fault rupture lengths. For example, the 1930 Salmas earthquake had an M_s 7.6 earthquake and only 30 km of known surface fault rupture.

These historical data suggest strongly that large earthquakes resulting in strike-slip surface fault rupture in southeast Turkey are generally greater than about M 7. Based on this historical precedent, we consider that the “largest reasonably conceivable earthquake” (i.e. CMCE) along the Yumrukaya fault is M_w 7.4. An M_w 7.4 earthquake on the Yumrukaya fault results in a median PGA value of 0.34g, and an 84th-percentile value of 0.50g at the Hakkari dam site. These values were calculated using the PGA attenuation relationship of Sadigh et al. [10].

An acceleration time history was developed for this MDE earthquake event. The attenuation relationships of Abrahamson and Silva [11] were used to develop a target acceleration response spectrum. Recorded acceleration-time histories were spectrally matched to these target spectra. For the M_w 7.4 earthquake occurring on the Yumrukaya fault 14 km from Hakkari, we selected the 0º component recorded at the Joshua Tree – Fire Station during the 1992 Landers earthquake (right-lateral, strike-slip, M_w 7.3). The Joshua Tree accelerogram was recorded on a rock site about 10 km from the surface rupture. Figure 4 shows the recommended spectrally matched acceleration time history for the CMCE M_w 7.4 earthquake occurring along the Yumrukaya fault 14 km northeast of the Hakkari dam and HEPP.

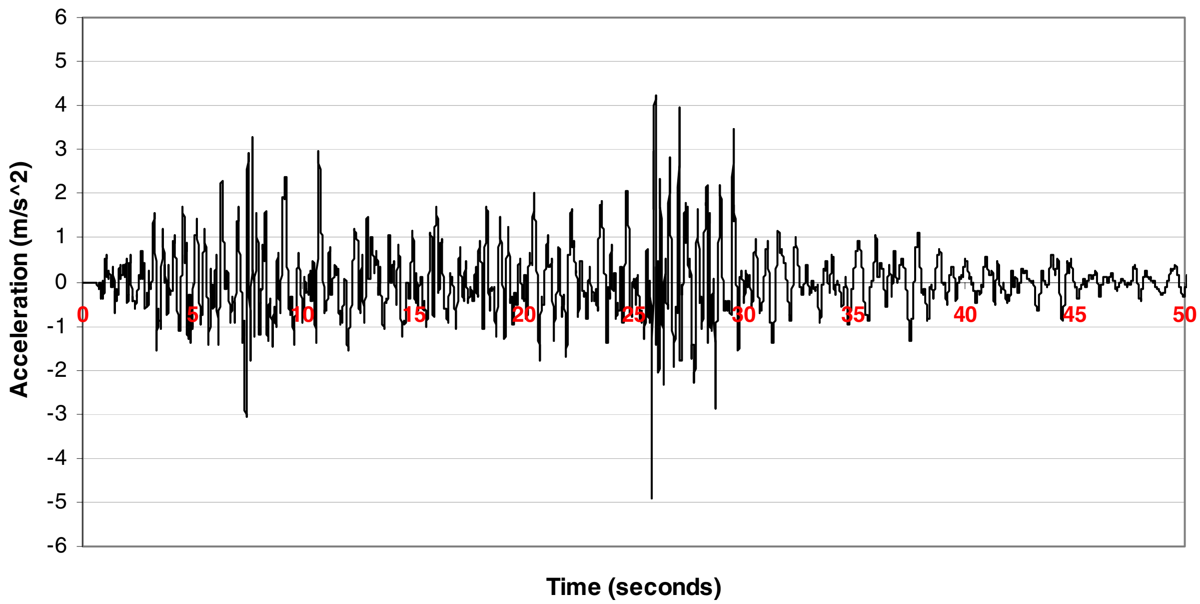

Figure 4: Acceleration time history for spectrally-matched ground motion for an M_w 7.4 earthquake occurring along the Yumrukaya fault 14 km northeast of the Hakkari dam and HEPP.

MDE for non-critical structures
A lower MDE is appropriate for non-critical structures where failure would not lead to failure of the dam and uncontrolled release of the reservoir. The MDE for these structures is the median ground motion with a 10% probability of exceedence in 50 years (average return period of 475-years). This return period for ground motions is in accordance with current Turkish Building Code requirements. Our probabilistic analysis results in a PGA of 0.26g for the MDE these for critical structures where failure would not lead to failure of the dam and an uncontrolled release of the reservoir.

Operating base earthquake
The operating base earthquake (OBE) is an earthquake that can reasonably be expected to occur within the 100-year service life of the project. The purpose of the OBE design is to protect against economic losses from damage or loss of service from all project structures. The performance requirement is that the project functions with little or no damage or interruption. The OBE is determined by probabilistic analysis. Based on ICOLD guidelines the OBE for HEPP is a PGA with a 50-percent probability of exceedence in 100 years (144-year return period). Our probabilistic analysis indicates a PGA of 0.17g for the OBE.

CONCLUSIONS

The Hakkari Consortium has undertaken site-specific field investigations and an assessment of the longer-term earthquake history in a broad region surrounding HEPP. Deterministic and probabilistic seismic hazard analysis has been used to provide a conservative assessment of earthquake hazards at HEPP. A conservative assessment is warranted because significant uncertainties remain, particularly the level of activity of large earthquake sources close to the dam site. This quantification of earthquake hazard and seismic design parameters permits completion of Phase-I design and final seismic design specifications for HEPP.

Critical structures where the MDE will apply include the:

- Main dam;
- Spillway and control gates;
- Power intake gates;
- Diversion tunnel plug; and
- Low-level outlet control works.

These critical structures will be designed to maintain their integrity during shaking from the CMCE (0.50g PGA; Figure 5). Some damage is expected and permissible.

Non-critical structures designed for a lower MDE of 0.26g PGA include:

- Spillway chute;
- Powerhouse and power equipment;
- Tunnels; and
- Switchyard.

All structures will be designed to withstand shaking from the OBE. DSI will review seismic design specifications to enable the project to move toward final design and construction

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