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Geotechnical and seismic design considerations for earth dams in the Philippines

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ABSTRACT

The Philippines, an archipelago with a population of more than 100 million, is one of the countries most exposed to various natural hazards: seismic hazards and climate-related hazards. In more recent years, significant progress was made in the development of design codes and standards, incorporating hazard mitigation and risk reduction, as well state-of-the-art approach and methodology for seismic analysis and design. These include the National Structural Code of the Philippines (NSCP) in 2015, and the Design Guidelines, Criteria and Standards (DGCS), published also in 2015 by the Department of Public Works and Highways (DPWH), the government's engineering agency. Most recently, in January 2018, the Philippine Earthquake Model – a probabilistic seismic hazard analysis of the Philippine archipelago, was published by the Philippine Institute of Volcanology and Seismology.

One of the major infrastructures built in the Philippines are earth dams, which are used for irrigation, hydropower, water supply, inland navigation, mining material storage, and flood control. The safety and resilience of existing dams, as well as new ones, has become a major concern in recent years, considering the occurrences of destructive earthquakes in the past 5-10 years.

This paper presents the current state of practice of geotechnical and seismic design of dams in the Philippines. Design codes (both international and local), design methodology, local conditions and area-specific design considerations are presented. The need for reasonably comprehensive geotechnical investigation and site-specific seismic hazard analysis was emphasized.

A case study involving the design of a 25-meter high water dam is presented.

Keywords: Geotechnical Considerations for Earth Dams, Site-Specific Seismic Hazard Assessment

1. INTRODUCTION

The Pacific Ring of Fire, containing a total of four hundred fifty-two (452) active volcanoes and over 75% of the Earth's active and dormant volcanoes, circles from South America, to Alaska, to Japan, to Philippines, and on to New Zealand. As a country that lies along the Pacific Ring of Fire, the occurrence of frequent seismic and volcanic activities makes the Philippines prone to several seismic-related hazards. In this context, design codes for engineering structures were developed, and are continually updated, to integrate these hazards in the engineering design.

This paper presents a review of the design considerations for dams in the Philippines, specifically Geotechnical and Seismic design considerations. Adopting the updated international design codes, and utilizing available advanced tools and techniques, a design methodology for dams (and appurtenant structures) in the Philippines is presented. Local conditions and area-specific design considerations are discussed – covering geological, seismic, and geotechnical considerations.

Deterministic and probabilistic seismic hazard assessment are used in establishing the seismic design parameters. A case study involving a 30-m concrete ogee dam is also presented.

2. EXISTING CODES

Dams are major infrastructures built in the Philippines for irrigation, hydropower, water supply, inland navigation, and flood control. Most of the existing large dams in the country have been designed under a number of different codes or design guidelines from other countries. There is no standardized design code for dams that has been established in the country so far. This leads to the utilization of international codes as the main basis of design.

The NSCP 2015 and the DGCS provide requirements for the parameters used in the design. This is supplemented by international design guidelines by the International Committee on Large Dams (ICOLD), United States Bureau of Reclamation (USBR) and United States Army Corps of Engineers (USACE).

3. EARTHQUAKE DESIGN PARAMETERS

Philippines is dotted with seismotectonic structures capable of producing strong earthquakes. Figure 1 shows the Seismicity Map of the Philippines which shows that almost every part of the country has a high chance of experiencing earthquakes.

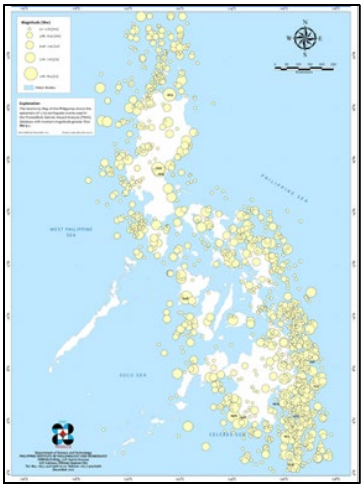

Figure 1. Seismicity of the Philippines (PHIVOLCS)

Two values for the magnitude of the earthquake will be used as design parameters. These two parameters for the magnitude of the earthquake are distinguished by their probability of exceedance or return period. The Maximum Credible Earthquake (MCE), as defined in the United States Army Corps of Engineers (USACE), is based on the highest intensity of earthquake recorded from a seismotectonic structure near the site. The other parameter for earthquake, Operating Basis Earthquake (OBE), is based on a probability of exceedance not greater than 50% for the project's life, typically 100 years for dams.

The Philippine Earthquake Model (PEM) by PHIVOLCS, provides the PGA data for rock sites (Vs30=760m/s) and stiff soils (Vs30=360m/s). All of these are calculated based on ground motions with 10%, 5% and 2% probabilities of exceedance in 50 years. In the design of dams, the 5% probability of exceedance is used for determining the parameter for the OBE and 2% for the MCE.

4. GEOTECHNICAL PARAMETERS

In the Philippines, the methodology of determining the stability of an earth dam is summarized by the following activities:

- Conduct geotechnical investigation
- Determine engineering soil parameters
- Perform stability analysis
- Perform seepage analysis

Typical soil investigation in the country involves the drilling and sampling of boreholes at the location of critical structures. Soils are sampled and tested using Standard Penetration Test (SPT) and coring for rocks. Soil/rock samples are tested in the laboratory using ASTM standard procedures to obtain the physical properties of each soil layer.

Parameters used in the calculation of geotechnical capacities are derived using correlations of the SPT resistances formulated on established geotechnical publications. The mechanical properties of the soil/rock such as unit weight (kN/m^3), angle of internal friction (^{0}), and cohesion (kPa) are determined. Subsequently, various tests may be performed to obtain soil/rock shear strength parameters such as direct shear test, triaxial test, unconfined compression test, etc.

Several methods may be used to calculate the stability of an earth dam such as Stability Charts by Taylor, Spencer, Janbu, and Bishop-Morgenstern. These charts are recommended for use on preliminary assessments only.

For a detailed analysis, Limit Equilibrium Method facilitated by computer programs are commonly used to establish the global stability of the dam. Varying pore water pressure ratio, from 0.1 (corresponding to low to moderate pore water pressure) to 0.4 (corresponding to high pore water pressure), and seismic coefficients shall be taken into account in determining the failure plane with the most critical factor of safety.

An acceptable factor of safety is based on various considerations such as the recurrent period of heavy rainfall, seismic activity, as well as the assessment of risk or hazard brought about by the slope failure. With these factors considered, recommended factors of safety for static conditions range from 1.2 to 1.5, and a value greater than unity (>1) for earthquake conditions.

A more advanced approach is to analyze the deformation of the structure by finite element method (FEM). Another important consideration in the design of dams relating to the behavior of the underlying soil is the groundwater seepage. It is necessary to ensure that the seepage of water is adequately considered in stability analysis. Seepage is analyzed using FEM based on the theories involving flow nets.

5. SEISMIC HAZARD ASSESSMENT

The design earthquake to be used in the design of the dams, particularly the structural design, can be obtained using two (2) types of assessment:

Deterministic Seismic Hazard Assessment (DSHA)
Probabilistic Seismic Hazard Assessment (PSHA)

5.1 Deterministic Seismic Hazard Assessment (DSHA)

In DSHA, the largest ground motion from any of the considered scenarios is used for the design ground motion. The approach is "deterministic" in that single values of the parameters (magnitude, distance, and number of standard deviations for the ground motion) are selected for each scenario.

Various attenuation models may be used in determining the peak acceleration. Increasingly being required by some lending institutions is the application of the New Generation Attenuation Relationships

(NGAR). This is the result of a multidisciplinary research program coordinated by the Lifelines Program of the Pacific Earthquake Engineering Research Center (PEER), United States Geological Survey (USGS), and Southern California Earthquake Center.

These groups developed Attenuation models for active shallow crust (ASC). These models were published in 2008 under the NGA-West project and were subsequently updated and improved under the NGA-West2 project in 2014. Four of these ground motion prediction equations (GMPE) are:

- Abrahamson, Silva, and Kamai (ASK14)
- Boore, Stewart, Seyhan, and Atkinson (BSSA14)
- Campbell and Bozorgnia (CB14)
- Chiou and Youngs (CY14)

The NGA-West2 GMPE's are generally developed to estimate the average horizontal component of peak ground motion and response spectra. A uniform spectral curve, usually at a damping ratio of 5% that is commonly used in the Philippines, can be obtained by assigning certain weighing factors to the values obtained from the different NGA-West2 GMPEs.

5.2 Probabilistic Seismic Hazard Assessment (PSHA)

PSHA is currently the most widely-adopted approach for describing seismic hazard. By considering all possible earthquake events and resulting ground motions, with their corresponding probabilities of occurrence, a full distribution of levels of ground shaking intensity and their associated rates of exceedance can be obtained. The plot of the intensity, which may be quantified by the spectral acceleration, against the rate of exceedance is typically called a hazard curve. Spectral acceleration amplitudes from hazard curves for different periods at a target rate of exceedance can be combined to form the uniform hazard spectrum.

In order to plot response spectra, PSHA models account for these uncertainties by using the Total Probability Theorem, which states that the overall probability of a system can be obtained by summing the individual probabilities of events that consider a particular uncertainty. From the Total Probability Theorem:

$$\lambda_a = \sum_{i=1}^{N_s} v_i \sum_{j=1}^{N_m} \sum_{k=1}^{N_r} P(S_a > a | m_j, r_k) P(M = m_j) P(R = r_k) \quad (2)$$

where Sa is the spectral acceleration, a is the ground acceleration of interest, λa is the mean annual rate of exceedance of any ground acceleration, v indicates seismic sources, and the P(Sa > a | mj, rk) term is a ground motion's probability of exceeding any ground acceleration given any combination of magnitude (m) and distance (r). Note that the probabilities for each seismic source are summed up together, and the overall probability is also a summation considering all seismic sources in the PSHA model.

Taking temporal uncertainties into account, PSHA models the probability of an earthquake's occurrence within a time frame, t, such that it follows the Poisson distribution:

$$P(S_a > a) = 1 - e^{-\lambda_a} \quad (3)$$

Seismogenic structures are key factors in PSHA (Wang, et al., 2016). These structures are delineated into zones wherein seismic activity within each zone can be treated as homogenous (Torregosa, et al., 2001) and can be attributed to a single source. The PSHA model is analyzed using the OpenQuake engine software developed by the Global Earthquake Model (GEM) Foundation. Pre-processing of earthquake data is performed by implementing the functions of the software's Hazard Modeller's Toolkit (HMTK).

6. CASE STUDY: 25M-HIGH DAM

A dam is proposed to be constructed in a mining area located in Masbate City. The main purpose of the dam is to supply water for the production mill as well as to the adjacent community.

Obtaining the design for a dam is a multidisciplinary process. In this case study, the results of the analysis of the other disciplines have already been considered and a preliminary design for the dam is subjected to analysis based on Geotechnical and Seismic Design considerations.

Presented below are the geotechnical and seismic design considerations used in the design and analysis of the dam.

6.1 Geotechnical Considerations

Seepage analysis is performed using a finite element software.

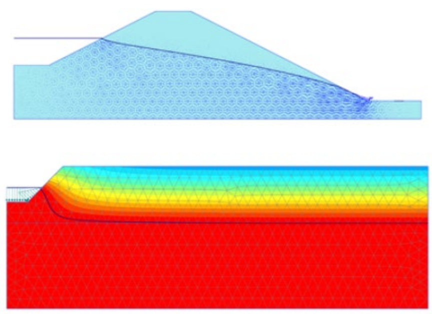

Figure 2. Sample seepage analysis model (PLAXIS 2D)

Designing the dam based on geotechnical conditions relies on the parameters discussed in section 4. In this case, the dam's foundation consisted of solid rock which mitigated seepage through the dam.

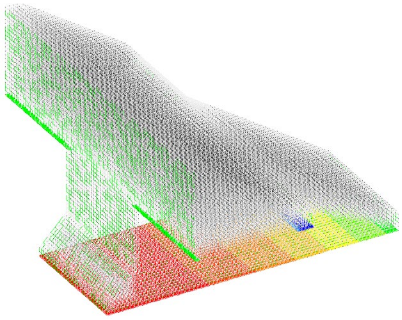

Figure 3 Bearing Pressure Analysis

Another consideration was the allowable bearing pressure for the dam and its stability. Since the foundation of the dam has been found to be composed of rock, the allowable bearing pressure was quite high.

Design the dam for seismic effects required a SHA, to produce the response spectras for different levels of earthquakes. These response spectra shown as Figure 5 and Figure 6 were employed to establish the forces acting on the dam.

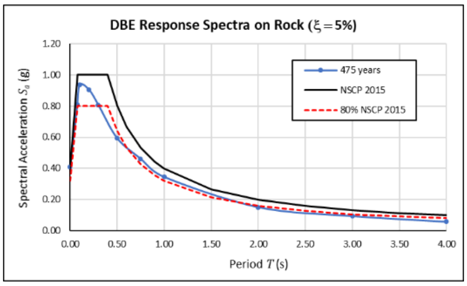

Figure 4 OBE Response Spectra with 5% Damping Ratio

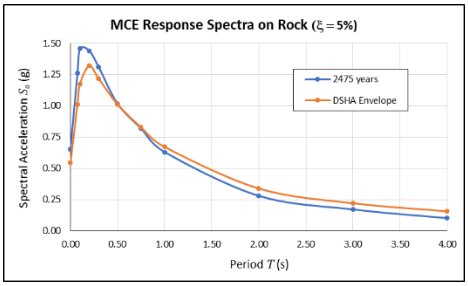

Figure 5 SHA MCE Response Spectra with 5% Damping Ratio

After employing the forces obtained from the other disciplines and from the SHA, the preliminary design of the dam proved sufficient in terms of seepage control, foundation adequacy (Figure 4) and stability.

The criteria used in determining this was based from the guidelines of USACE

7. CONCLUSION

Currently, the design and analysis of large scale dams in the Philippines is based on a number of international codes and standards. However, due to the unique geographic setting of the country, numerous design factors should be further considered in the design of dams. Further development of a local design code for dams is imperative.

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