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TECHNOLOGICAL ADVANCES AND LEARNED LESSONS FROM LAST GREAT EARTHQUAKES AND TSUNAMIS IN THE WORLD

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FUNDAMENTALS OF THE EFFECTS OF EARTHQUAKES ON THE GROUND AND STRUCTURES

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SUMMARY

Important mining projects are being developed in our country, which require a structural design not only for their buildings, process plants and various facilities, but also for their earth and mining waste structures, where the concepts of performance-based seismic design of structures are being implemented. The effects of an earthquake on the ground and on structures are based on the existing knowledge of seismology, geotechnics, geophysics, soils dynamics and structural behavior. To the author, it is clear that this is the current situation in many countries. The inertial model which aims at estimating seismic forces, the basis of structural design, has been questioned in the past few years since the way it represents the behavior of structures during an earthquake seems to be very limited, particularly when the structure collapses on soft soil, where damages increase significantly causing sometimes large numbers of victims. The work submitted herein is founded on the study of ground motion during an earthquake, considering not only the acceleration but also the displacements generated by the earthquake. Two case studies are presented based on experience acquired in the past years in the mining industry and alternative, different structure failure mechanisms are proposed with a recommendation to review and complement the current seismic design concepts.

INTRODUCTION

Performance of the foundation soil and soil structures under seismic loads has been discussed since 1987 by the International Society of Soils Mechanics and Geotechnical Engineering (ISSMGE) and its recent contributions were summarized during the last International Conference of Performance-Based Design in Geotechnical Earthquake Engineering, Kokusho [1].The knowledge of ground motion and deformations induced by an earthquake is the most important stage of performance-based design, particularly for soft soil. A quick review of the ground motion and structure performance during the earthquakes that occurred in the world indicates that structures under a conventional seismic design are incapable of withstanding large deformations, especially when founded on soft soil, figure 1 and 2. Performance-based design is based on the criterion of the tolerable ground motion in accordance with the structures' design criteria and the application of appropriate methodologies to determine them.

Ground Motion Caused by an Earthquake

According to Newmark [2], the effect of an earthquake on structures, the following should be considered:

a) All of the earthquake's characteristics, being the peak acceleration not necessarily the main factor of seismic response.

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Figure 1, 2: Evidence of excessive displacement on very superficial concrete slab foundation (the design was based on the inertial model and horizontal force of the Peruvian Technical Standard E0.30 for Earthquake Resistant Design, and did not consider the effect of the horizontal and vertical displacements during the earthquake). Earthquake 8.15.07 in Pisco, Peru.

b) The effect of the earthquake's velocity, displacement and duration may be of equal or greater importance to determine the seismic response.
c) All of the earthquake's characteristics, being the peak acceleration not necessarily the main factor of seismic response.
d) The effect of the earthquake's velocity, displacement and duration may be of equal or greater importance to determine the seismic response.

Velocity (cinematic energy) is the most important variable to study motion as well as displacement (potential energy). Both are indicators of the intensity of the earthquake and therefore of potential damage to structures. During the occurrence of an earthquake and the resulting ground motion, there are moments during which the velocity is zero and there is maximum displacement. The earthquake's intensity (energy) should be assessed compared with its maximum velocity or maximum displacement (Fig. 3). From this viewpoint, acceleration is not representative of the earthquake's intensity (energy) and can therefore not necessarily be the basis for the seismic design of the structures.

It should be highlighted that large accelerations recorded in recent earthquakes did not necessarily result in large structural or geotechnical damage. For instance, Kokusho [3] indicated that during the earthquakes in San Fernando (1971) and Northridge (1994) in the USA, the peak ground accelerations (PGA) of 1.0G and 1.8G did not cause major structural damage in the surrounding areas. During the 2004 earthquake in Nigata, Japan, the 1.7G acceleration in Tokamachi did not cause the major damage as had been anticipated either, and many similar cases have been recorded. This indicates that acceleration may not be a parameter governing damage to structures, compared to other parameters such as displacement or velocity, as Kokusho stresses [3].

The inertial model has its origin in the rigid body mechanics and is intended to estimate seismic forces in the current design methods which are earthquake resistant; this is why it has been questioned in recent years, Villarreal [5], as it is said to represent the behavior of structures during an earthquake in a very limited way, particularly on soft soil.

The study of ground motion caused by an earthquake, where seismic waves experience the phenomenon of amplification in passing from bedrock to less dense soil, indicates the following:

a) The energy which is generated by the earthquake and which propagates through seismic waves, does so through elasto-plastic behavior.

b) The (non-recoverable) inelastic deformation component is the dissipated seismic energy, which is called ground damping.
c) Softer, less dense soils dissipate larger amounts of energy since they suffer larger unrecoverable deformations than hard soils.
d) The energy is transmitted more slowly in soft soils compared to hard soil. Superficial seismic waves in soft soil, for example, can travel at velocities between 50 and 200 m/s, while in hard rock they propagate at a velocity exceeding 2000 m/s, which is 10-40 times faster.
e) The impedance of the physical medium associated with the difference in density between soil and bedrock transforms the bedrock's kinematic type energy into energy of the potentially soft soil deforming type.

Seismic Ground Amplification

The analytic methods used to study seismic amplification of the site in order to rigorously evaluate the effect of an earthquake consider the following stages:

1) Establishment of an appropriate time-history record of bedrock accelerations to model the dynamic response.
2) Modeling of the unidimensional dynamic response using the results of the previous stage and applying dynamic modeling using the SHAKE program, Schnabel [4].

Time-History Record of Accelerations in Bedrock

The records used resulted from the processing records from 17 earthquakes occurred in Peru (Table 1). From the assessment performed, processed records of seismic behavior accelerations in the country were obtained. Based on the assessment of the predominant period, 06 records were selected as representative of the subduction and continental sources seismicity (Table 2).

Unidimensional Dynamic Response Modeling

In the unidimensional dynamic analysis model, it is assumed that earthquake accelerations will occur in the bedrock, making up a unidimensional ground column. From the bedrock, horizontal shear waves propagate vertically and reflect on the deposit surface. The dynamic properties of the materials that make up the profile were estimated from the results of measurement tests of surface shear waves, Vs, Japanese Society of Civil Engineers [5], Kramer [6] and Towhata [7]. Dynamic properties, such as shear modulus and damping, were estimated from the existing technical literature (Hardin, 1972; Seed and Idriss, 1970; Seed et al., 1984; Vucetic and Dobry, 1991).

Dynamic Parameters

The dynamic behavior was assessed unidimensionally through geophysical profiles, which have provided average values for surface shear wave velocities Vs(30), in accordance with the IBC. Measurements of velocity profiles for surface shear waves were made through multichannel analysis of surface waves (MASW) Park et al., 1999; Xia et al. 1999; Miller et al., 1999.

Case 1: The effect of an earthquake on gravel soil

The soil is composed of gravel silty (GM, GW-GM, GP-GM and SM) with angular to sub-angular particles and 4" - 7" diameter blocks. S.P.T. tests ranged from 10 to 35. Density varies from loose to medium dense up to a depth greater than 50 meters. Four (04) geophysical profiles were evaluated resulting in average surface shear wave velocity values Vs(30) of 340, 380, 400, 440 and 780 m/s respectively. The seismic response analysis was carried out using the short period accelerations record (0.1 to 1 sec.) and long period accelerations (up to 1 and 3 sec) of the Pisco earthquake (2007) and Yurimaguas earthquake (2005), respectively; the accelerations record was scaled to 0.22 g. The results of the seismic amplification analysis at ground surface level are shown in Tables 3 and 4.

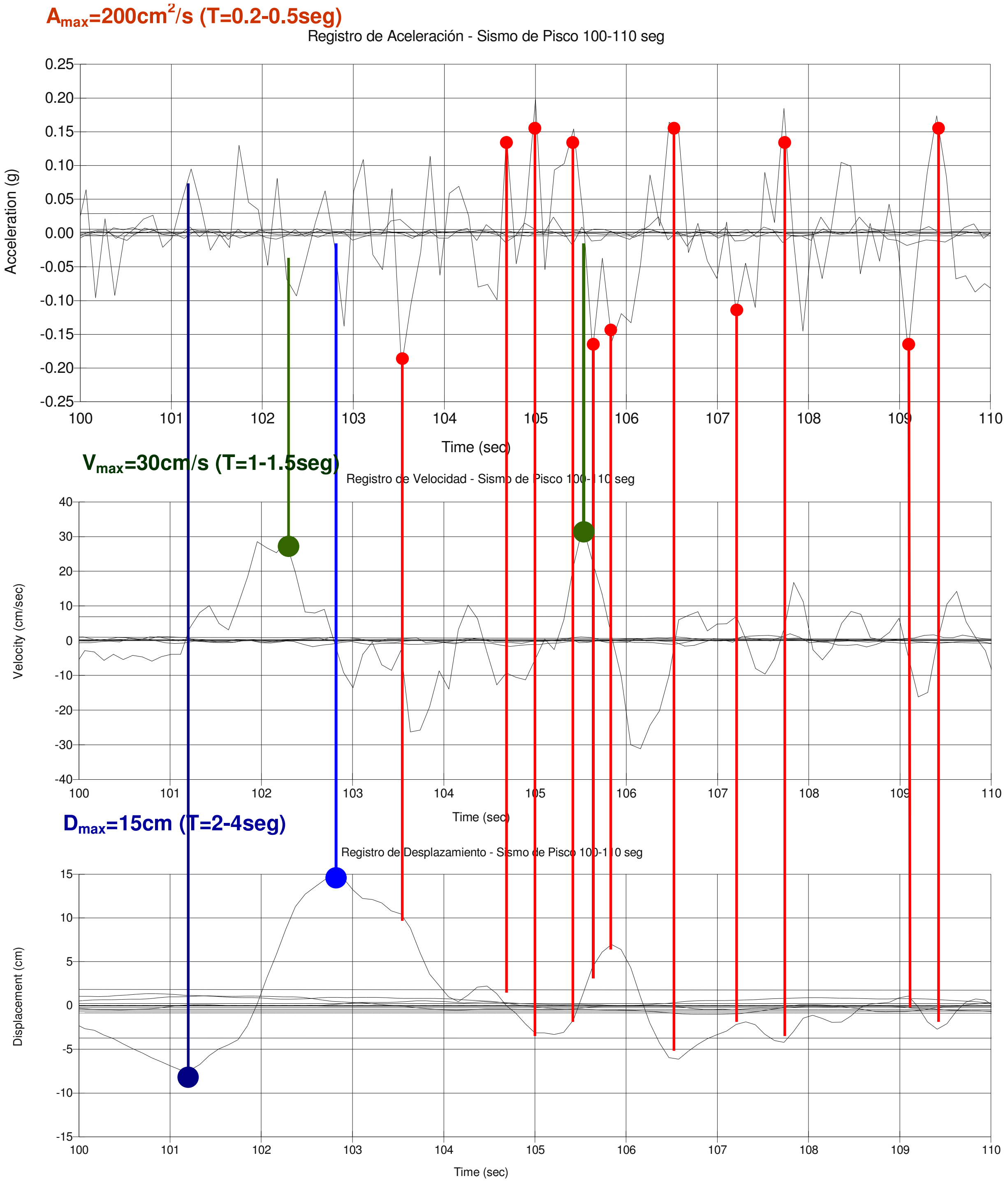

Figure 3: Acceleration, velocity and maximum displacement (by integration in surface soft soil), during the 10 most intense seconds (100-110) of the Earthquake 8.15.07 in Pisco.

Table 1: Calibrated and Evaluated Earthquake Records

Station	Earthquake	Date	Magnitude	Strike	Dist. Hypoc.
U.N.S.A. Arequipa	Tarapacá	Jun-13-05	ML=7.2, Mw=7.8	E-W	422
Characato-Arequipa	Tarapacá	Jun-13-05	ML=7.2, Mw=7.8	E-W	414
Characato-Arequipa	Pisco	Aug-15-07	ML=7.0, Ms=7.9, Mw= 8	E-W	520
Callao	Pisco	Aug-15-07	ML=7.0, Ms=7.9, Mw= 8	E-W	200
C.D. Lima-CIP	Pisco	Aug-15-07	ML=7.0, Ms=7.9, Mw=8	E-W	200
CISMID-UNI	Yurimaguas	Sep-25-05	ML=7	E-W	706
CISMID-UNI	Pisco	Aug-15-07	ML=7.0, Ms=7.9, Mw=8	E-W	200
La Molina-Lima	Yurimaguas	Sep-25-05	ML=7	E-W	713
La Molina-Lima	Pisco	Aug-15-07	ML=7.0, Ms=7.9, Mw=8	E-W	200
G.R. Moquegua	Arequipa	Jun-23-01	Mb=6.9, Mw=8.3	E-W	340
G.R. Moquegua	Tarapacá	Jun-13-05	ML=7.2, Mw=7.8	E-W	324
Moquegua	Tarapacá	Jun-13-05	ML=7.2, Mw=7.8	E-W	323
Moquegua	Tarapacá	Jun-13-05	ML=7.2, Mw=7.8	E-W	320
Moyobamba-San Martín	Yurimaguas	Sep-25-05	ML=7	E-W	146
U.N. Jorge Basadre-Tacna	Arequipa	Jun-23-01		E-W	220
U.N. Jorge Basadre-Tacna	Tarapacá	Jun-13-05	ML=7.2, Mw=7.8	E-W	231
U. Privada Tacna	Tarapacá	Jun-13-05	ML=7.2, Mw=7.8	E-W	232

Table 2: Representative Earthquake Records

Earthquake (recorded)	acceleration recorded	displacement calculated	S. Fourier period
Tarapacá 2005 (Arequipa)	0.13	3.0	<0.1
Pisco 2007 (Lima)	0.05	2.5	0.3-1.5
Arequipa 2001 (Moquegua)	0.30	5.0	0.4-1.0
Tarapacá 2005 (Moquegua)	0.05	0.3	0.1
Yurimaguas 2005 (Moyobamba)	0.14	7.0	0.3-4.0
Tarapacá 2005 (Tacna)	0.12	2.8	0.2-0.5

Table 3: Case 1: Acceleration Amplification Factors

Profile	Vs(30)	Pisco (2007)	Yurimaguas (2005)
1	340	1.5	1.6
2	380	**3.5**	2.1
3	400	**3.1**	2.1
4	440	1.8	2.1
5	780	2.0	1.5

Table 4: Case 1: Displacement Amplification Factors

Profile	Vs(30)	Pisco (2007)	Yurimaguas (2005)
1	340	1.1	1.3
2	380	1.1	1.2
3	400	1.0	1.2
4	440	1.1	1.2
5	780	1.0	1.1

Case 2: The effect of an earthquake on sandy soil

The soil is composed of sand and silt (SM, ML, SP-SM), of recent formation. S.P.T. tests ranged from 4 to 30. Density ranges from loose to medium dense to a depth greater than 30 meters; there is no ground water table. Three (03) geophysical profiles were assessed which resulted in average surface shear wave velocity values Vs(30) of 200, 240 and 270 m/s, respectively. The seismic response analysis was carried out using the accelerations record of the earthquakes in Pisco and Yurimaguas; the acceleration record was scaled at 0.40 g. Tables 5 and 6 shown he results of the seismic amplification analysis.

Table 5: Case 2: Acceleration Amplification Factors

Profile	Vs(30)	Pisco (2007)	Yurimaguas (2005)
6	200	1.1	1.1
7	240	1.4	1.6
8	270	1.8	1.7

Table 6: Case 2: Displacement Amplification Factors

Profile	Vs(30)	Pisco (2007)	Yurimaguas (2005)
6	200	1.3	**2.0**
7	240	1.3	**2.2**
8	270	1.2	**2.0**

The real case study of seismic wave propagation in the ground shows the following:

a) The predominant vibration or seismic motion period of the ground is associated with the soil density and rigidity.

b) The predominant vibration period of the bedrock ranges from 0.1 to 1 second. The predominant vibration period in soft soil may reach values from 1 to 3 seconds.

c) Energy damping or dissipation is larger in soft soils.

d) Degradation or reduction of rigidity in soft soil is very significant, reaching up to 10-20% of the initial rigidity for 1% deformation.

e) Strong, short-period earthquakes (between 0.1 and 1 second) in hard soil cause accelerations above 1.0G, associated with the acceleration amplification phenomenon. Strong, long-period earthquakes (between 1 and 3 seconds) in soft soil cause deformations exceeding 1%, generating loss of rigidity, loss of strength and excessive increase of displacements, from 10 to 25 cm, associated with the displacement amplification phenomenon due to the seismic resonance.

f) The inertial model cannot be applied to structure behavior in soft soil. Instead, ground displacement should be considered during an earthquake, or a combination of both. In the proposed kinematic model, apart from the inertial model, other failure mechanisms should be evaluated, where horizontal shear stresses are not necessarily dominant.

Seismic Amplification Study in Lima

According to Predes, an earthquake with a magnitude of Mw 8.0, similar to the one that occurred in Pisco, with an acceleration of 0.35-0.40g, is expected to occur in Lima in the next years. In Table 7, CISMID-UNI [8], proposes the following seismic amplification factors for accelerations, to be applied in accordance with the earthquake resistant standard based on the inertial approach. In 2009, WAPMEER (World Agency for Planetary Monitoring and Earthquake Risk Reduction) made preliminary estimates of losses due to possible earthquakes in Lima, and concluded that if 50% of the people are located inside buildings at the time of an earthquake, between 7,000 and 30,000 people will die. In the worst case scenario, which is at night, with an 80% occupation of buildings, the number of fatalities would range from 10,000 to 50,000, Predes [9].

Table 7: Seismic Amplification in Lima - CISMID-UNI (2003)

Soil Type	Seismic Amplification Factor
Type I: Hard soil, old conglomerate, dense and consolidated.	1.0
Type II: Intermediate soil, La Perla, San Miguel, La Molina, Los Olivos, San Juan de Miraflores, Surco. Sandy and silty sediments of limited thickness, less than 10 meters.	1.2
Type III: Soft soil, San Juan de Miraflores, Chorrillos, Callao, Villa El Salvador, Magdalena. Sandy and silty soil with a thickness greater than 10 meters.	1.4
Type IV: Very soft soil, Ventanilla, Chorrillos, San Juan de Miraflores, Villa El Salvador. Coastal sand, loose sand with presence of a ground water table.	1.4

For the aforementioned estimates, a magnitude 8 earthquake was used. An amplification factor for strong ground motion was considered based on the CISMID-UNI microzoning map. The results of these studies suggest in the near future to review, complement the seismic microzoning studies, the earthquake resistant methodologies, the Technical Standard for Soils and Foundations and for Earthquake Resistant Design.

Failure Mechanism and Solutions Associated with the cinematic Model

In the cinematic model, based on the movement induced by an earthquake in the structures, not only horizontal, but also gravitational (vertical) forces are produced because it is made possible by the ground motion. Moreover, it has been determined that horizontal acceleration in soft soil is controlled (decreased) by the impedance of the phenomenon of seismic wave propagation. The failure mechanism in soft soil is associated with the gravitational forces that generate shear strengths in the vertical plane of any structure (Figure 4,5,6), associated with the vertical and slow undulating motion of the ground (for a large predominantly long period). It is estimated that the vertical shear strengths will reach magnitudes which are much greater than those currently estimated, based on the inertial model; therefore, there is still a large amount of damage current engineering cannot control, unless special structures are used as in the case of the Latin American Tower located in the soft zone of Mexico City. This is a 44 story building founded on piles, which was built in 1956. It withstood the M=7.7 earthquake on July 28, 1957; the M=8.1 earthquake on September 19, 1985 and the M=7.9 earthquake on March 20, 2009. It is estimated that shear strengths in conventional structures are of such magnitude that other alternatives will be searched in order to reduce not only shear strengths through light and flexible structures, but also to reduce the structure motion by replacing or reinforcing the foundation soil using non-conventional materials such as geosynthetics, Tatsuoka [10] and The Japanese Geotechnical Society [11] or considering deeper foundations.

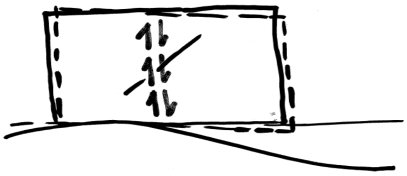

Figure 4: Damage caused by vertical displacements and excessive differentials in the ground during an earthquake.

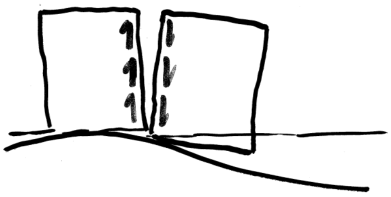

Figure 5: Structure failure caused by vertical shear stress concentration.

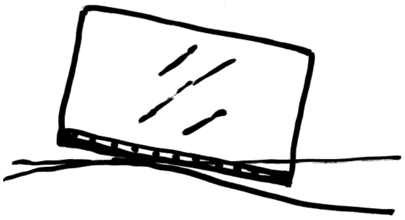

Figure 6: Failure caused by turn over in structure founded on a surface concrete slab.

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