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SYNOPSIS: The methodology used for an initial seismic zonation is briefly introduced and then developed to provide details of a microzonation presently in progress for the Costa Oriental del Lago Maracaibo coastal dyke protection system. The microzonation is focussed towards the evaluation of dynamic site response of selected representative soil profiles. The results of the study are to be applied for evaluation of seismic stability and deformation mechanisms for the coastal dyke system with a view to defining remedial measures for critical sections of the linear earth structure.

INTRODUCTION

In 1982, MARAVEN and INTEVEP commenced a program of studies to evaluate the reliability of the coastal protection system on the east coast of Lake Maracaibo (Costa Oriental del Lago de Maracaibo, or COLM). The principal objective of the study was to provide a seismic zonation of the area of interest, including an evaluation of the possible remedial measures which could be applied, if necessary, to ensure the stability of the protection system under earthquake loading conditions.

The area known as the COLM is an oil-producing region consisting essentially of three principal production fields: from north to south they are called Tía Juana, Lagunillas and Bachaquero. Oil production first commenced in the region more than 50 years ago. However, the extraction of petroleum from the shallow reservoirs has given rise to problems of surface subsidence in the major areas of production, in many cases to such an extent that the areas are now situated below lake level. In order to avoid flooding of populated centers and areas where oil installations have been constructed, the construction of a coastal dyke protection system was initiated along the lake edge in the areas most affected by subsidence. Obviously, as production continued, the magnitude and extent of the area affected by subsidence has also increased.

At first, the small dykes were constructed with little or no control in terms of the foundation or fill materials. Later, based on the seismotectonic characteristics of the area, it became apparent that, due to the continued rates of subsidence, some higher levels of engineering control were necessary. Furthermore, it was also suspected that the foundation soils were potentially susceptible to liquefaction, based on expected levels of ground shaking for the region. Consequently, a series of studies were initiated to evaluate the risks associated with a possible dyke failure as a result of liquefaction of the foundation soils.

The studies performed in the three subsidence areas to provide a seismic microzonation and the evaluation of the remedial measures necessary to increase, to an acceptable level, the integrity of the coastal dyke system is discussed in this paper.

STUDIES PERFORMED

After having identified the magnitude of the subsidence problem, a mayor effort was made to improve the dyke design in order to avoid future problems of flooding of the oil installations. This aside, the design of the dyke was based on static concepts with little or no consideration given to the dynamic aspects of the problem. In various opportunities, the susceptibility to liquefaction of the granular foundation soils was evaluated, but with little or no conclusive results being obtained. Partly, this was due to the sparsity of seismic data for the area, which did not allow for a maximum design acceleration to be specified. On the other hand, the granular soils in the area contain important percentages of fines (up to 40%) and not much published information was available as to the effect of fines content on the overall dynamic behavior of the system. As the dykes continued to extend both vertically and laterally (dictated by the development of the subsidence bowl) it became more and more important to evaluate the integrity of the system subject to earthquake forces.

Based on the above, MARAVEN began the process of contracting specific studies aimed at resolving uncertainties in the seismicity of the region and the geotechnical reliability of the dyke-foundation system. At the seismic and geotechnical macrozonation level, the chronological sequence of the work performed can be summarized as:

- initial phase of geotechnical borings in order to generate typical soil profiles along the length of the dykes in the three subsidence areas
- definition of the geological and tectonic setting of the region close to the subsidence bowls and evaluation of the seismic sources capable of producing levels of ground shaking that could affect the stability of the dyke-foundation system
- review of available data regarding the historical and instrumental seismicity of the area in order to provide preliminary estimates of the possible range of design accelerations
- installation of a portable microseismic network to evaluate background levels of seismicity
- execution of deep seismic refraction studies along the east coast of the lake to provide a crustal model for the area, with the objective of improving the attenuation law and knowledge of seismicity of the zone
- completion of a second stage of geotechnical studies, including specialized in situ and laboratory testing, to provide a geotechnical characterization of the foundation soils
- testing of scale models in a geotechnical centrifuge for evaluating trends in the dynamic behavior of the dyke-foundation system and determining possible failure mechanisms in the presence of liquefiable foundation soils
- installation of a permanent seismometer network in the region, providing direct data transmission to an acquisition center and real time data processing
- installation of an automatic strong-motion accelerometer network

- initiation of a neotectonic study to determine the characteristics of the major faults in the area and evaluate their associated activity
- finalization of the geotechnical characterization with emphasis on the determination of dynamic soil parameters for pre- and post-liquefaction analyses

The results of all the above studies have been incorporated in the seismic zonation. Recently a pilot study has begun to extend the results obtained so far to the microzonation level; the microzonation level in this case consisting of detailed information at each of the three subsidence areas (approximately 40 km² in extent). The microzonation extends the previous more generalized results and takes into account the effect that the variations of soil profiles may have on the local dynamic response.

The procedures used in the microzonation process for the Tía Juana subsidence area are briefly considered here. Further field and laboratory studies are being performed to reduce the uncertainty in the parameters used for the zonation and to extend the microzonation studies to the remaining two subsidence areas.

BASIS OF THE MICROZONATION

The microzonation is based on the following geotechnical response conditions:

- surface ground accelerations
- liquefaction susceptibility of sands, silty sands and silts
- pre- and post-earthquake (pseudo-static) slope stability
- post-seismic slope deformations
- definition of necessary remedial measures for critical dyke sections

The general procedures used in the microzonation, from geotechnical characterization to definition of necessary remedial measures will be discussed briefly in the following sections.

GEOTECHNICAL CHARACTERIZATION

Based on the previous field and laboratory data, the Tía Juana coastal dyke (a total length of 7 km) was subdivided into 15 geotechnically different profiles, the difference in the first instance being determined on the variation of soil types in the profile. In certain cases, more specific (less general) profiles were included in this preliminary characterization. A typical example of this would be where localized peat or organic clays/silts were present. These types of soils are known to exert considerable influence on the dynamic response. The depth limit for the characterization was between 20 m and 30 m and determined by the availability of data.

The field data used for the characterization included the results of standard penetration tests (SPT), in situ vane tests (FVT), piezocone tests (CPTU) and downhole and crosshole shear wave velocity determinations (DH-XH V_S). Laboratory test data included both classification and strength and deformation parameters.

For a given soil profile, the average shear wave velocity, V_S*, can be calculated if the variation of Vs with depth is known:

$$V_S^* = \frac{\Sigma (V_S)_i \cdot H_i}{\Sigma H_i} \qquad (1)$$

In an area where the thickness of the soil profile is approximately constant (as can be assumed for the COLM area), the dynamic soil response can be characterized by the average shear wave velocity alone, rather than the fundamental period of the profile. This was the initial criterion used to determine "similar-type response" profiles in the area. Since the soil response is controlled by the soil characteristics, each representative soil profile was also evaluated in terms of the percentage of different soil types in each. As demonstrated by Vucetic and Dobry (1991), modulus degradation can be correlated broadly with soil plasticity and so this was also used as an index parameter for the initial characterization.

In general terms, the dyke foundation soils can be divided into three principal units:

- an upper layer of loose to medium dense silty sand and non-plastic silts, 2.5 m to 4.5 m thick
- a middle layer of very soft to soft silty clay, occasionally organic, to a depth of approximately 13 m, and
- a lower layer of firm to stiff clay, interbedded with dense sand

In Tía Juana, the soft clay layer contains only very localized peat layers of limited lateral extent and so they are not of primary importance for the microzonation.

At various locations along the dyke, in situ measurements of shear wave velocity by the crosshole technique have been performed. In order to extend this information to other areas where V_S measurements are not available, the data have been correlated with index parameters such as N_{SPT}, S_u or q_c (Echezuría and Sully, 1986). Typical relationships derived for COLM data are:

$$G_{max} = (2000 \text{ to } 2300) S_u \qquad (2)$$

$$V_S = 77 (N_1)^{0.33} \qquad (3)$$

Equation (3) is compared with other published relationships in Fig. 1.

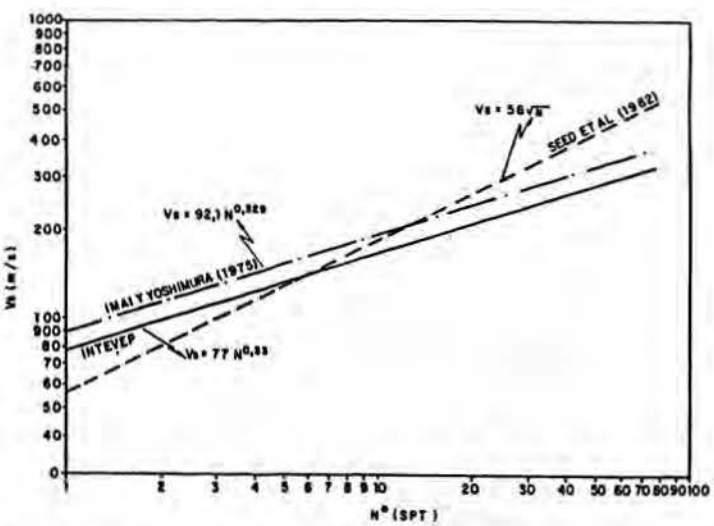

Fig. 1 Published correlations between V_S and N_{SPT}

DEFINITION OF INPUT MOTION

The input motions for the microzonation studies were determined from seismic hazard studies performed in the area. For the Tía Juana region, the variation of maximum bedrock acceleration as a function of return period is shown in Fig. 2. From this figure, the value of maximum base acceleration for any useful life and probability of exceedence can be determined (typical values are indicated on the figure). For the COLM coastal dykes, a 3% probability of exceedence in a 100 year expected life has been chosen as the design condition and corresponds to a bedrock acceleration of 0.225 g.

In order to perform the microzonation study, not only the maximum acceleration is required, but also information regarding the duration and frequency content of the generated earthquakes that may affect the area. This information was determined during the initial seismotectonic investigations. Based on these studies, a duration of around 20 seconds was selected as representative with epicentral distances of the order of 100 km to 150 km. Both synthetic and real acceleration records were then evaluated to provide input acceleration records representative of both near- and far-field sources.

The depth of application of the basal acceleration was determined from a sensitivity study based on information from deep borings (down to 500 m) previously performed in Tía Juana. The variation of the small-strain shear modulus with depth was evaluated from the results of in situ and laboratory resonant column test data. Both lower and upper bound limits were defined. A series of response analyses were then performed to study the effect of the variation of "bedrock" depth on the surface accelerations and frequency content. Bedrock was defined at depths varying from 150 m to 500 m. The modulation of the selected input motions was then evaluated at a depth of 50 m, these time history records being the output at 50 m depth obtained from each of the response analyses with differing input bedrock depths .

In order to reduce the thickness of the soil profile to be analyzed, the modified 50-m depth records are used as input records for the microzonation study. In this way, the "new bedrock depth" is assigned at 50 m and only the soil variations of interest in the microzonation study (between the ground surface and 50 m depth) need to be modelled in the analysis. The 50 m record is an unbiased average based on both soil modulus variations and depth to bedrock. The frequency content variation of the different records is also evaluated and selected to represent the average response as a result of propagation between the depth of application and the 50 m level. As well as average values, the variations of both peak acceleration and frequency content are considered in the input motions. The maximum acceleration for the input record (to be applied at 50 m depth below each profile) was determined to be 0.084 g for the 3000 year design earthquake condition. (In all cases, the peak acceleration showed a reduction from the "bedrock level" to the 50 m level (Fig. 3); the degree of reduction being slightly larger for the deeper input levels.)

Once the 50 m input acceleration time histories had been evaluated, the dynamic response for the representative near-surface (0 m to 50 m) soil profiles was evaluated.

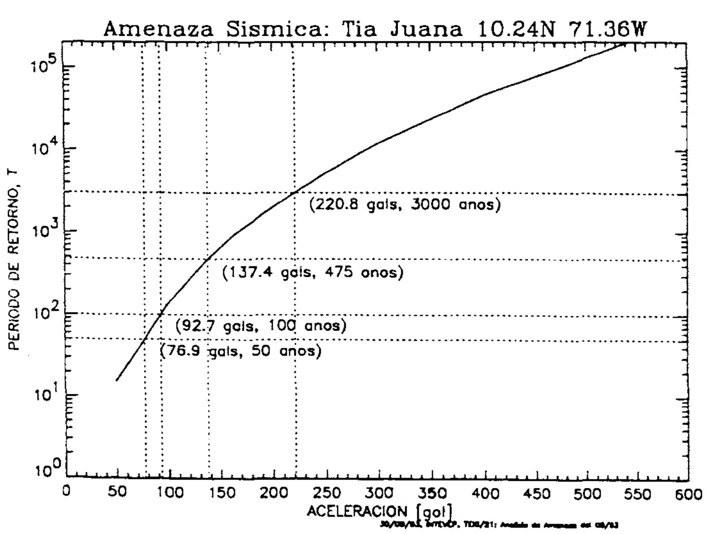

Fig. 2 Seismic hazard for Tía Juana area

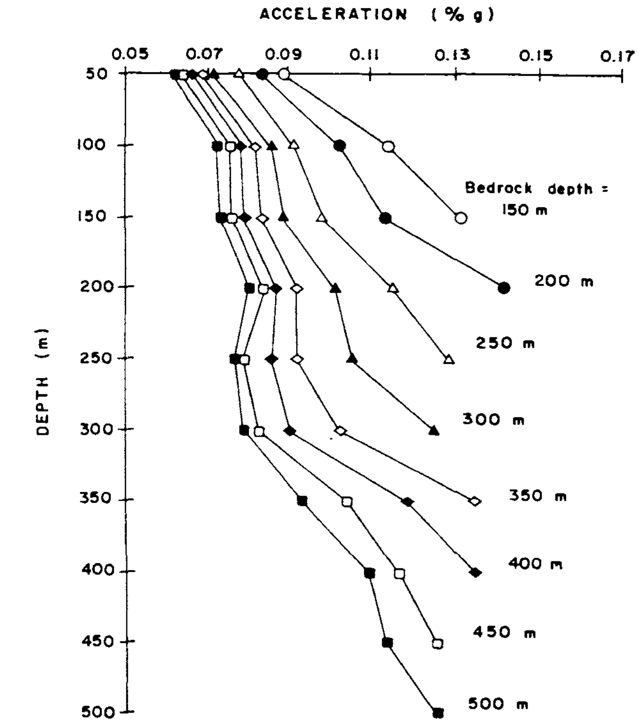

Fig. 3 Variation of seismic response for deep profiles

DYNAMIC SITE RESPONSE ANALYSES

The site response analyses were performed using the recently modified version, SHAKE91 (Idriss and Sun, 1992), of the well-known program SHAKE (Schnabel et al., 1972). The SHAKE91 program performs an equivalent linear elastic analysis which incorporates modulus reduction according to average strain levels induced by the applied ground motion. The Vucetic and Dobry (1991) degradation curves were used as were the curves for variation in damping ratio. Parametric studies were again used to evaluate the range of response according to variations in the input data and soil properties. Typical variations in the average shear wave velocity in the Tía Juana region, as well as soil type variations for the defined representative soil profiles are shown in Fig. 4. As stated earlier, both real and synthetic time histories were used representing near- and far-field sources. Results obtained from these type of sensitivity analyses have demonstrated the importance of soil type and parameter variations on the response for the COLM soils (Fernández, 1993).

Evaluation of Liquefaction Potential

According to preliminary results, the majority of the near-surface granular soils in the Tía Juana polder will undergo initial liquefaction. Whether or not the behavior will be contractive with subsequent strength loss is being presently evaluated by laboratory tests. However, for first phase studies, a residual strength of 1 t/m^2 or a strength ratio, $S_{u_{ss}}/\sigma_v'$, equal to 0.12 (whichever was the largest) was assigned to the liquefied soils for evaluation of pseudo-static stability.

Evaluation of Post-Seismic Deformations

Post-seismic deformation analyses were performed using the computer code DYNARD, developed by Woodward Clyde Consultants, and licensed to MARAVEN/INTEVEP. Additional analyses were also contracted to provide validation of the obtained results using the program TARA-3FL (Finn, 1992).

Definition and Implementation of Remedial Measures

Stability and deformation analyses were performed for each characteristic dyke and foundation system for both pre- and post-seismic conditions. The assumptions and parameters for these static and pseudo-static analyses have been discussed by Sully et al. (1993). Backanalyses of case histories of failures due to liquefaction have been performed to verify the approach and parameters used for both stability (Geoproyectos, 1992) and deformation analyses (Sully et al., 1993a). When it became apparent that certain sections of the dyke would not meet the stability and deformation criteria established for the dyke-foundation system, an evaluation of alternative types of remedial measure was performed. Initially, the addition of downstream berms was implemented as the most cost-effective approach. In some areas, however, where land restrictions do not permit construction of the downstream berm, more localized ground improvement methods were used; in this case the installation of stone columns. In some cases, an upstream rip-rap berm is also added to improve stability in this area and reduce the magnitude of the estimated post-seismic deformations.

CONCLUSIONS

The methodology and results of a seismic zonation and later microzonation have been presented with emphasis on the evaluation and remediation of a linear earth structure, critical to the continued oil production in the Lake Maracaibo area of Venezuela. However, the results of this study have also been used for implementing contingency plans and planning the social and economic development of an area of important industrial activity. Although in this instance the results have only been discussed with respect to the coastal dyke system, they can be easily extrapolated to other areas away from the dyke. A detailed geological and geotechnical evaluation is presently underway to consolidate the available information and make it readily accessible.

The application of the results obtained has demonstrated the usefulness of the microzonation approach, both for understanding and evaluating the controlling geotechnical and seismotectonic parameters, as well as allowing for the implementation of timely and cost-effective remedial measures. The introduction of microzonation was useful for correctly understanding the possible dynamic response variations due to localized subsoil variations; an important factor in the COLM area where the geological constraints on deposition have given rise to a vertically and laterally variable sequence of sediments of varying consistency.

Studies are currently continuing to provide additional data to reduce uncertainties in present knowledge. The permanent strong motion and microseismic networks are also nearing completion and will provide further data for verification of the tectonic model and attenuation law being used. In specific areas of the dyke, local seismic monitoring stations are being installed (accelerometers and piezometers) for calibration of the dynamic response analyses. In addition, the results of the microseismicity study performed by the CETE-FUNVISIS-INTEVEP-MARAVEN group will also provide information that may be used to calibrate the small-strain dynamic response of typical soil profiles.

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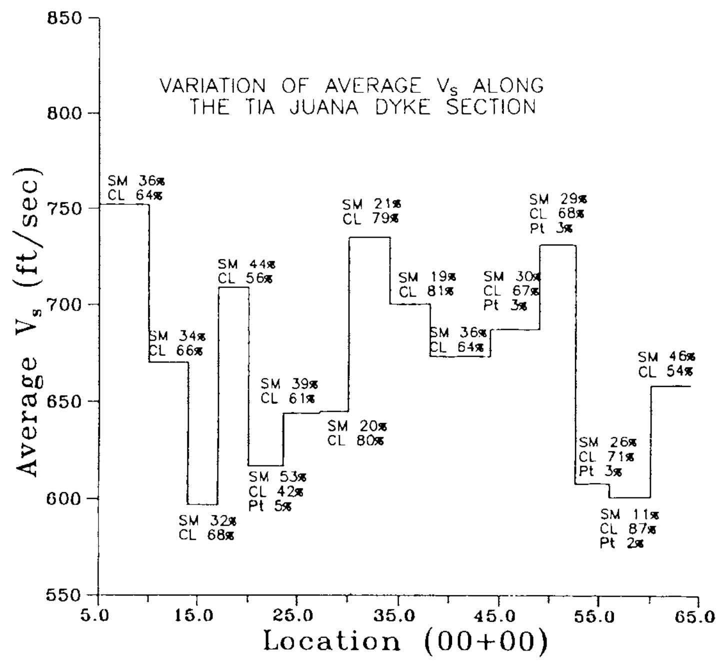

Fig. 4 Characteristics of established representative soil profiles

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