NUMERICAL MODELLING OF SEISMIC RESPONSE OF CANTILEVER EARTH-RETAINING STRUCTURES

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ABSTRACT

In current engineering practice the seismic design of earth retaining structures is usually carried out using empirical methods. Dynamic earth pressures are calculated assuming seismic coefficients acting in the horizontal and vertical directions calculated with either the Mononobe-Okabe or the Wood method depending on the anticipated movement that the structure will undergo when subjected to earthquake loading.

This paper illustrates the results of a research investigation aimed to assess the appropriateness of using the Mononobe-Okabe method for determining the dynamically-induced lateral earth pressures on the stem portion of concrete, flexible cantilever retaining walls sustaining a granular backfill. A series of non-linear dynamic finite element analyses have been performed using the computer program DIANA (DIsplacement ANAlyzer). The analyses included a static-phase of stress initialization caused by placement of soil and incremental construction of the wall followed by dynamic analyses.

Soil response was simulated using an elasto-plastic, Mohr-Coulomb constitutive model. The influence of variables such as wall stiffness and strength parameters of the backfill were investigated through a parametric study. Special attention was given to the selection of seismic input in order to represent realistic ground motion scenarios corresponding to different levels of severity. Dynamic earth pressures obtained from numerical simulations were compared with those determined using pseudo-static approaches through a series of benchmark tests. Co-seismic and post-seismic displacements of the wall were also calculated using simplified pseudo-dynamic methods. Reliability of the results obtained with DIANA was assessed through a comparison with available results of analyses performed using the finite difference-based program FLAC (Fast Lagrangian Analysis of Continua).

***Key words*:** Retaining walls, Mononobe-Okabe, Seismic earth pressure, Elasto-plastic, Mohr-Coulomb.

1. INTRODUCTION

Regardless the multitude of studies that have been carried out over the years, the dynamic response of earth-retaining walls is far from being well understood. There is, in current engineering practice, a lack of conclusive information that can be used in design method. The most commonly used methods to design earth-retaining structures under seismic conditions are force-based equilibrium approaches like the pseudo-static analysis (e.g. Mononobe-Okabe [1]) and pseudo-dynamic techniques (Steedman and Zeng [2]), and displacement-based procedures such as the sliding block method (e.g. Richards and Elms [3]). In the limit-state methods of analyses in which the wall is considered to displace or deform sufficiently at the base to fully mobilize the shearing strength of the backfill.

Even under static conditions, prediction of actual retaining wall pressures and deformations constitute complicated soil-structure interaction problem. The dynamic response of even the simplest type of retaining wall is therefore a quite complex phenomenon. It depends on the mass and stiffness of the wall, the backfill and the underlying ground, as well as the interaction among these components and the nature of the seismic input motions.

The purpose of this study was to develop a finite element numerical model to throw light into understand the dynamic behavior of cantilever earth-retaining structures, in particular to find the magnitude and distribution of dynamic lateral earth pressures, as well as the displacements induced by horizontal ground shaking. In all the analyses, the soil was assumed to behave as a homogeneous, elasto-plastic medium with a Mohr-Coulomb failure criterion. The wall was assumed to behave as linear elastic material. The numerical model for the wall and surrounding soil has been developed using DIANA [4], a commercially available finite element program.

The results obtained with DIANA were compared with results obtained from pseudo-static analysis using the procedure by Mononobe-Okabe and, to some extent, the results obtained with FLAC by Green and Ebeling [5], [6] for the same case-study. The two models, namely, the DIANA model and the FLAC model by Green and Ebeling, have the same meshing and material properties (mass density, friction angle) with the only exception of shear wave velocity profile. This latter is taken constant and equal to the weighted average along the height of the values in Green and Ebeling. As shown later all qualitative trends observed by Green and Ebeling are also found with the DIANA analyses.

2. EARTH-RETAINING STRUCTURE-SOIL SYSTEM

Figure 1 shows the soil-wall system that has been studies in this paper. The height of the flexible wall is 6.1m. The backfill and foundation soil is assumed to be medium-dense, cohesion-less, compacted fill. Its most important geotechnical properties are as follows: mass density: γs = 19.6 kN/m^3; effective angle of internal friction: φ' = 40˚. The water table is assumed located well below the foundation of the wall and thus the analyses are performed assuming dry soil.

The properties of the concrete and of the reinforcing steel used for designing the wall are as follows: concrete unit weight : γ_c = 23.6 kN/m^3; concrete compressive strength: f'_c = 27.6 MPa; steel yield strength: f'_y = 413.4 MPa.

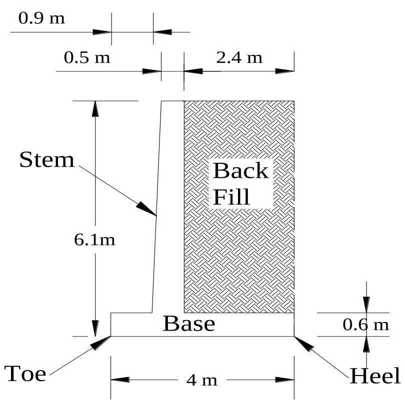

Figure 1: Dimensions of the wall-soil system studied in this work

3. NUMERICAL MODEL

The finite element model set up in DIANA consists of the upper 9.1 m of the wall-soil system and it contains the wall, the backfill and 3m of the underlying natural soil below the foundation of the wall. The model extends laterally for approximately 26.0 m to include 9.35 m of existing soil in front of the wall and about 16.65 m of the backfill/existing soil behind the wall (see Figure.2).

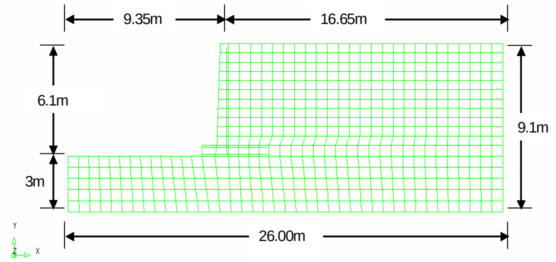

Figure 2: Mesh of FEM model developed using DIANA

The soil and the wall are modeled using eight-nodes quadrilateral isoparametric plane-strain elements. The size of the elements varies from 0.50 m to 0.60 m. A total of 688 elements are used in the model. An elasto-plastic constitutive model, with Mohr-Coulomb failure criterion, is used to model soil response under both static and dynamic loading conditions. Plane-strain elements are also used to model the concrete retaining wall with linear elastic material.

To simulate realistic earth pressures developed at the back of the wall as it deforms during construction, the wall-backfill system is "numerically constructed" in DIANA similarly to the way an actual earth-retaining structure would be constructed in reality. The backfill is placed in 0.50 m lifts, for a total of 12 lifts with the model being brought to static equilibrium after each increment. Table 1 illustrates the values of the geotechnical parameters used in this study for the foundation soil and backfill. The small-strain fundamental frequency of the retaining wall-soil system in the DIANA model is estimated to be approximately 9 Hz.

Table 1: Geotechnical parameters used in the FEM model for foundation soil and backfill

Parameters	Value
Poisson's ratio (-)	0.26
At-rest pressure coefficient (-)	0.36
Young's modulus (MPa)	163.13
Effective friction angle (deg)	40º
Density (kg/m3)	2000
Cohesion (MPa)	0.00
Dilation angle (deg)	0º

Three acceleration time-histories were used for the seismic analyses of the earth-retaining structure shown in Figure 1 and they include the 1940 Imperial Valley earthquake (California), the 1999 Chi-Chi earthquake (Taiwan) , and the 1995 Hyogoken-Nambu (Japan), corresponding to low, medium and high Peak Ground Acceleration (PGA), respectively.

4. DISCUSSION

Dynamic analyses were performed using the acceleration time-histories described above. The results obtained from DIANA were compared with those determined using pseudo-static method (i.e. following the approach by Mononobe-Okabe).

Following Green [7] the dynamically-induced lateral earth pressures acting on the stem of the wall and the section along the heel (see Figure 1) were computed by assuming constant stresses within the element. The corresponding lateral earth pressure coefficient ($K_{j,DIANA}$) could then be back-calculated at time increment j from DIANA results using the following expression:

$$K_{DIANA} = \frac{2 \cdot P_{DIANA}}{\gamma_t \cdot H^2 \cdot (1 - k_v)} \qquad (1)$$

Where, P_{DIANA} is the resultant of stresses computed by DIANA and acting on the stem or the section along the heel of the wall, γ_t is the total unit weight of the backfill, H is the height of the wall, and k_v is the vertical inertial coefficient (assumed in this study equal to zero). Equation (1) is used to compute K_{DIANA} values at times corresponding to the peaks in the time-history of the horizontal inertial coefficient (k_h) acting towards and away from the backfill. A plot of the computed KDIANA values versus k_h is shown in Figure 3. Also shown in this figure are the lateral dynamic earth pressure coefficients (active: K_{AE}; Passive: K_{PE}) computed using the Mononobe-Okabe expressions for the wall-soil system (Okabe [8]; Mononobe [1]) and Wood [9] solution for rigid wall.

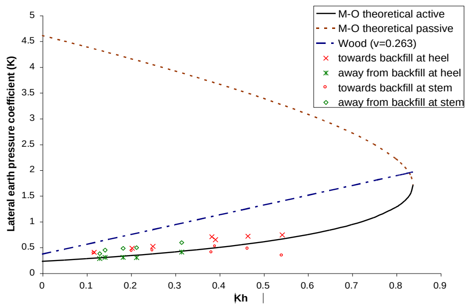

Figure 3: Comparison of DIANA and Mononobe-Okabe dynamic lateral earth pressure coefficients

The stress distribution along the stem of the wall before the dynamic analysis was very close to the theoretical active earth pressure distribution calculated using Rankine theory (see Figure 4). Figure 5 shows that at the end of the dynamic analysis and for all three seismic inputs of Table 1 the active pressure distribution is close to the values associated with the at-rest soil pressures.

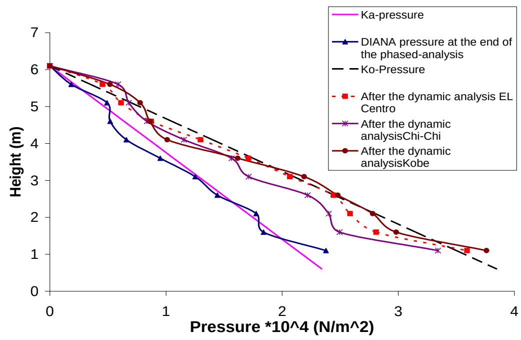

Figure 4: Comparison of pressure distributions along the stem of the wall before and after the dynamic analysis

In general, the values of K_{DIANA} values are somewhat higher than the Mononobe-Okabe active lateral earth pressure coefficient. This phenomenon is discussed in detail by Green [7] where a similar soil-wall system is analyzed with the computer program FLAC. It is due to the failure wedge in the backfill that is composed of several failure wedges rather than a single wedge as inherently assumed in the Mononobe-Okabe theory.

The bending moments along the wall were computed using the pressures due to the dynamic forces on the wall. Figure 5 shows the maximum bending moments' envelopes along the wall for all three records, together with the moment distribution at the end of the excavation phase.

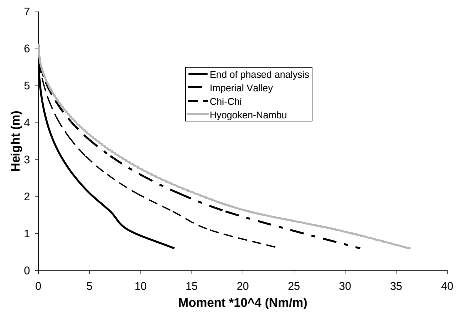

Figure 5: Maximum bending moments' envelopes

5. SUMMARY AND CONCLUSIONS

This paper illustrates a preliminary investigation onto the seismic behavior of flexible cantilever RC retaining wall, with horizontal dry granular backfill. A finite element model of the system is built using DIANA finite element program. For the foundation soil and backfill elasto-plastic constitutive model with Mohr-Coulomb failure criterion was used.

The results from this case study show that the pressures induced on the wall stem are larger than to those predicted by the Mononobe-Okabe method. The reason for this deviation may be attributed to a) the relative flexibility of the structural wedge and b) to the non-monolithicity of motion within the driving soil wedge. Both situations are neglected in the Mononobe-Okabe method. The dynamic response of the wall-backfill system is such that there is an incremental increase from active to at-rest earth pressure conditions in the residual stresses imposed on the stem of the retaining wall.

The conclusions drawn from this study may not apply to retaining wall system of differing geometry and/or material properties. Further research is required in order to draw more general conclusions regarding the appropriateness of the Mononobe-Okabe method to evaluate the dynamic pressure induced under seismic conditions on the cantilever walls.

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