Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0015

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

2D equivalent linear analysis for the seismic vulnerability evaluation of multi-propped retaining structures

Analyse linéaire 2D équivalente pour l'évaluation de la vulnérabilité sismique des structures de soutènement multi-étayé

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ABSTRACT: The evaluation of the seismic behaviour of underground structures represents one of the most actual seismic geotechnical and structural engineering research topics about the study of the complex phenomena of soil-structural interaction. In the last decades, different types of simplified and numerical approaches have been developed for the correct analysis of the seismic vulnerability of these important infrastructures and a series of laboratory tests for the seismic behaviour characterization of the soils (resonant column test, etc.) and of the coupled soil-structure system (centrifuge test, etc.) have been conducted, especially after the recent strong earthquakes where the underground structures have been subjected to significant damages. In the same way, in the last few years, the International Codes are beginning to pay attention to the concepts of the seismic design of these structures.
Despite the significant development of knowledge, described above, still remain open several uncertainties of the correct reproduction of the underground structures behaviour under seismic load.
In this paper, the evaluation of the seismic behaviour of a multi-propped retaining structure was conducted, considering the soil-structure interaction effects. The results of the 2D equivalent linear analysis are analysed in terms of bending moment acting on the concrete retaining walls.

RÉSUMÉ: L'évaluation du comportement sismique des structures souterraines représentent un des sujets de recherche les plus courants sismique, géotechnique et de construction, qui concerne l'étude du phénomène complexe de l'interaction sol-structure. Pendant les dernières décennies, différents types d'approches simples et numeriques ont été développés pour une analyse exacte de la vulnérabilité sismique de ces infrastructures importantes et encore une série de tests de laboratoire pour la caractérisation du comportement sismique du sols (test de colonne résonnante etc.) et du système couplé du sol-structure (test de centrifugation etc.) ont été menées, après le fort tremblement de terre où les structures souterraines ont subi des dommages importants. De la même manière, pendant les dèrnieres années, les Codes Internationales ont commencé a prêter plus d'attention aux concepts de désign sismique de ces structures. Malgré la considèrable connaissance, décrit ci-dessus, il y a quand même de l'incertitude sur la correcte reproduction du comportement des structures sous charge sismique. Dans cet article, il a été mené l'evaluation du comportement sismique des structures de soutenement multi-etayé, considérant que les effets de l'interaction sol-structure. Les resultats de l'analyse linéaire 2D equivalente sont analysées en termes de moment de flexion agissant sur les murs de soutènement en béton.

Keywords: Underground structures, Soil-structure interaction, Finite element analysis, Seismic vulnerability.

1 INTRODUCTION

Underground structures can be grouped into three broad categories (Bickel, 1996), each characterized by distinct design features and construction methods: bored or mined tunnels, cut and cover tunnels and immersed tube tunnels.

Unlike surface constructions, underground structures were considered, for a long period, practically invulnerable to earthquakes. This consideration about underground structures safety, however, has been changed after some of them suffered serious damages caused by earthquakes, including the 1995 Kobe (Japan), the 1999 Chi-Chi (Taiwan) and the 1999 Kocaeli (Turkey) earthquakes (Hashash et al., 2001).

Damaging effects of earthquakes on underground structures can be classified into two main groups: damages caused by vibratory motion (shaking) of the ground and damages due to ground failures.

This study has the purpose of determining the most important aspects of the soil-structure interaction effects on underground structures subjected to seismic loads, taking as case study a metro station characterized by a multi-propped retaining structure.

2 CASE STUDY

The metro station is characterized by a rectangular plan (132.16 x 29.00 meters) and it is subdivided into 3 different zones (Figure 1). Each zone is, further, subdivided into 3 different levels.

The principal structural elements that characterized the metro station are the concrete retaining walls, 1 m thick, and a series of concrete circular columns, 1.2 m diameter, positioned in a regular grid 14.70 x 12.00 m. The foundation of the columns consists of circular concrete piles, 1.8 m diameter and 9 m deep Figure 2. The materials mechanical properties of the structural elements are shown in Table 1.

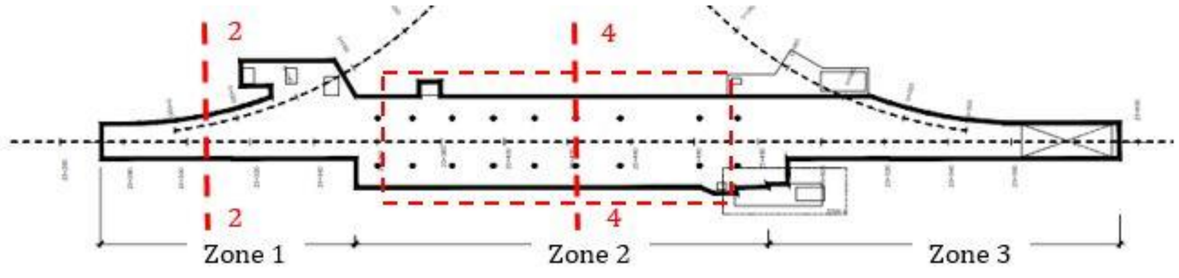

Figure 1. Metro station plan

The investigations around the area of the Metro station have shown the sequence of four lithological units with different mechanical properties (Table 2). The dilatancy, considered in this study, is equal to zero.

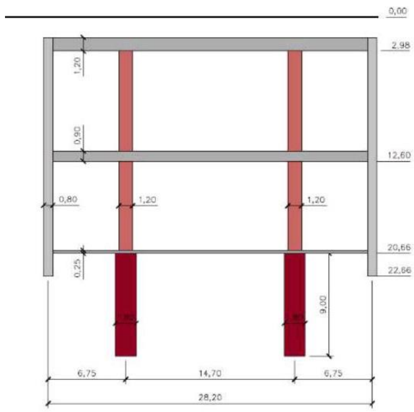

Figure 2. Section 4-4

Table 1. Structural elements mechanical properties

Structual elements	**Concrete (f_{ck}) [MPa]**	**Steel (f_{yk}) [MPa]**
Columns	40	420
Piles	40	420
Walls	30	420

Table 2. Lithological units mechanical properties

Soil type	**h_i (m)**	**γ_d (kN/m^3)**	**c (kPa)**	**φ (°)**	**E (MPa)**	**G (MPa)**	**V_s (m/s)**
back-fill	1.7	15.2	0	28	17	7	200
gravel	0.9	19	15	34	42	16	400
gravel	6.1	20	27.5	36.5	82.5	31	460
gravel	51.3	21	40	39	183	70	750

2.1 Numerical Analysis

The analysis of the seismic behaviour of the metro stations is carried out considering static and dynamic loads. Two finite element models representing both structure and soil are implemented. The two bidimensional models implemented by MIDAS GTS software represents the section 4-4 of the Zone 2 (Figure 2) and the section 2-2 representing both Zone 1 and Zone 3 (Figure 3).

The FEMs are characterized by plane strain elements and an example of geometry and the relative computation grid are shown in Figure 4. The maximum size of computation mesh elements has been fixed in order to allow the correct propagation of harmonic with 15 Hz maximum frequency, which is the maximum frequency of the seismic signals adopted in this study, according to Kuhlemeyer & Lysmer, 1973. The formulation to optimize the size of the mesh is given in Pagliaroli et al., 2007. For each model, the boundary conditions are the following: vertical supports in the base nodes to restrain the vertical displacements and horizontal supports in the lateral nodes of the mesh to permit vertical soil settlements. In dynamic conditions, in order to minimize reflection effects on vertical lateral boundaries of the grid, free field boundary conditions available in MIDAS GTS library have been used. The structure is schematized by means of linear elastic beams while for the soil an elastic perfectly plastic model with Mohr-Coulomb strength rule, characterized by the mechanical properties shown in Table 2, was adopted. The soil hysteretic behaviour was modeled using the shear modulus decay curves given by Seed & Idriss, 1970 and Stokoe et al, 2013.

2.1.1 Static loads

The static loads considered in the analysis are described in the following:

- dead load on the sides of the station equal to 50 kN/m^2 due to the presence of existing buildings and streets;
- dead load in correspondence to the station equal to 20 kN/m^2 due to the presence of the streets;
- self-weight of the structure and the soil.

The structural condition of the metro station under the considered static loads are determined by performing a construction stage analysis, taking into account all the main phases involved in the construction of the station and in order to reproduce the excavation and the realization of the structure with cut and cover method, before the dynamic stage of the analysis. The principal construction phases are:

- the execution of a first excavation;
- the realization of the diaphragm walls and of the wells for the realization of the foundation piles;
- the realization of the top cover slab made of reinforced concrete and 1.2 m thick;
- the execution of a second excavation;
- the realization of the intermediate slab made of reinforced concrete and 0.6 (section 2-2) - 0.9 m (section 4-4) thick;
- the execution of a third excavation;
- the realization of the concrete bottom slab 0.25 m thick;
- the road surface restoration.

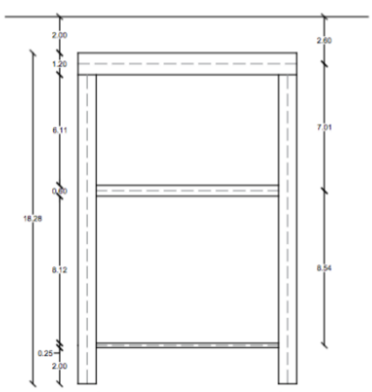

Figure 3. Section 2-2

2.1.2 Seismic actions

The seismic design approach of underground structures is generally characterized by two different type of earthquake events the maximum design earthquake (MDE) and the operating design earth-quake (ODE) typically defined as:

MDE: is the earthquake event that has a return period of several thousand years. It has a small probability of exceedance, approximately 5 % or less, during the 100 years facility life. It is aimed at public life safety.

ODE: is the event for which recurrence interval is several hundred years; the probability of exceedance of this event is approximately 40 % during the facility life. It is aimed to guarantee full functioning of the structure. The response of underground structures should, therefore, remain within the elastic range.

In this case, two different type of artificial seismic accelerograms are taking into account for the evaluation of the seismic behavior of the metro station, according to the study of seismic risk of the project area and to the values shown in Table 3: one seismic event characterized by a return period equal to 1000 years in order to represent the ODE (Figure 5) and another seismic event characterized by a return period equal to 2450 years in order to represent the MDE (Figure 6), according to GB50909-2014. The recording has been cor-rected with a low-pass filter at the cut-off frequency of 15 Hz using DEGTRA.

2.2 Static analysis

The static analysis carried out by the application of all the before mentioned vertical loads has pointed out the characteristic behaviour of the retaining walls of the Metro Station structure: it appears similar to a double multi-span (simply supported) beams.

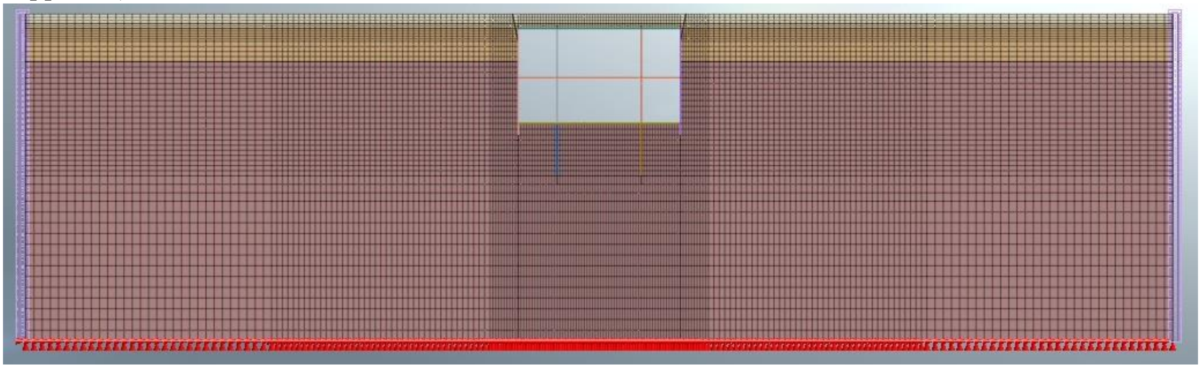

Figure 4. FEM computation mesh grid

Table 3. Parameters for the generation of the synthetic seismic accelerograms

Return Period	1000/2450 y
Magnitude	8.1
Fault Distance	45 km
Fault Type	Subduction
V_s	1050 m/s
PGA	0.49/0.77 g

The structural conditions of the Metro Station under the considered static loads are determined by performing a construction stage analysis, taking into account all the main phases historically involved in the construction of the station.

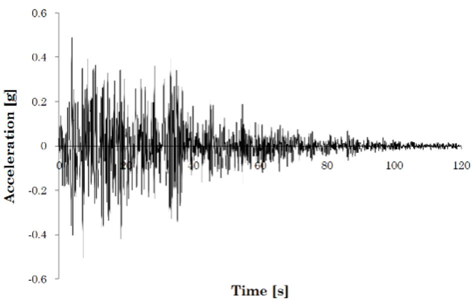

Figure 5. ODE seismic input

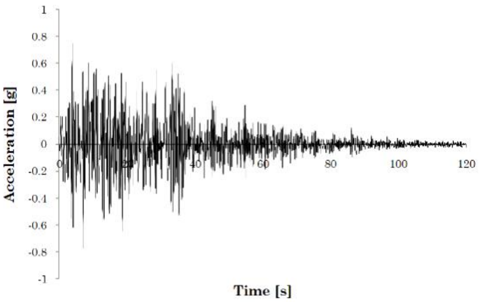

Figure 6. MDE seismic input

2.2.1 Section 4-4

Known the geometry and the values of the static loads, the results are obtained in terms of bending moments acting on the retaining walls (Figure 7).

The maximum values of the bending moment acting on the retaining walls obtained in static conditions is equal to 600 kNm.

2.2.2 Section 2-2

The characteristics of the Section 2-2 FEM are shown in Figure 3. The considerations about FEM dimensions and properties are the same of the Section 4-4 FEM.

Also in this case, the bending moment acting on retaining walls is obtained after a construction stage analysis and the maximum value of bending moment acting on the retaining walls is near 600 kNm.

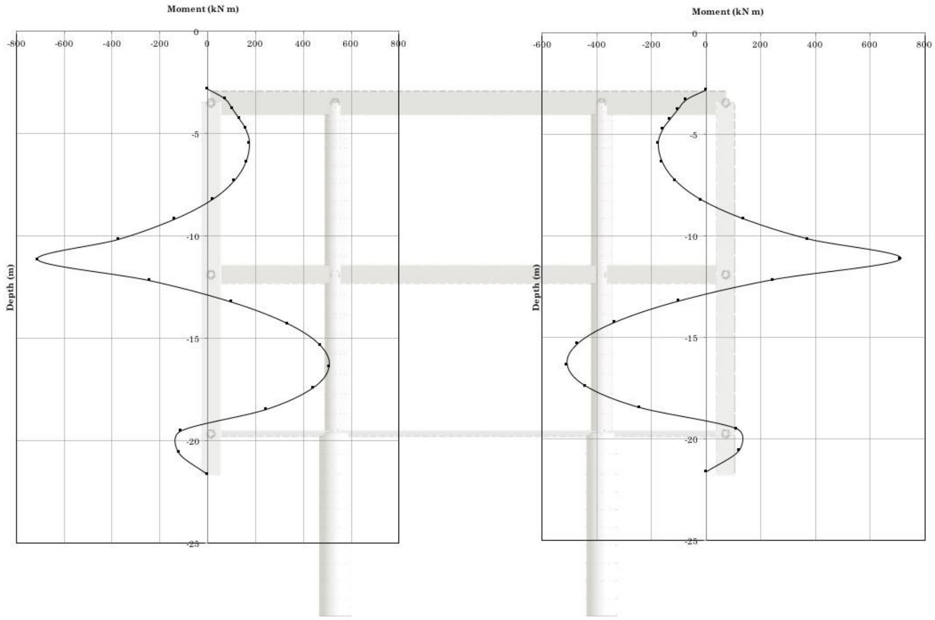

Figure 7. Moment acting on the Section 4-4

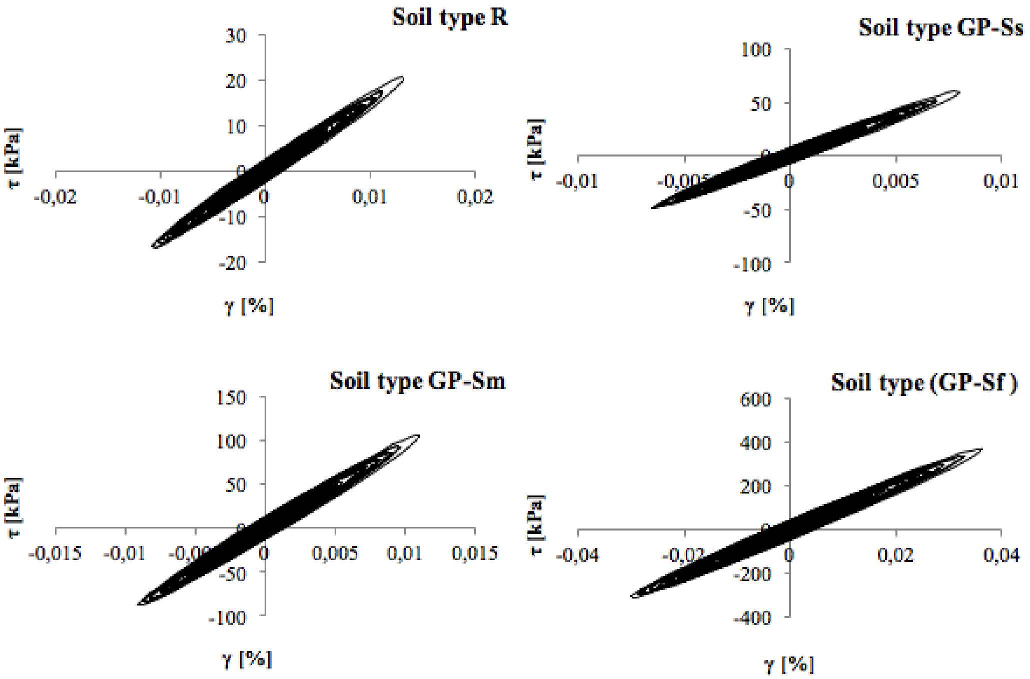

Figure 8. τ -γ cycles

2.3 Dynamic analysis

The dynamic analysis is performed, after the final step of the construction stage described before, by using 2D Equivalent Linear analysis, considering the seismic inputs described in previous paragraph. The present analysis is repeated for all the two above described characteristic sections.

Figure 8 shown an example of τ -γ cycles obtained, respectively, at a depth of 1 meter (soil type R), at 2.6 meters (soil type GP-Ss), at 8.7 meters (soil type Gp-Sm) and at 22 meters (soil type GP-Sf) for the seismic input characterized by a return period equal to 1000 years.

The results showed that the Metro Station remain within the elastic range for a seismic input characterized by a return period equal to 1000 years. On the contrary, for the seismic input characterized by a return period equal to 2450 years, only the section near the intermediate slab shows localized plastic deformation.

For the Section 2-2 the same considerations could be made.

3 CONCLUSIONS

Seismic response of the Metro Station to two seismic inputs characterized, respectively, by a return period equal to 1000 years and 2450 years shows an elastic behavior of the retaining walls for a seismic input characterized by a return period equal to 1000 years and for the seismic input characterized by a higher return period, the station shows localized plastic deformations only in the section near the intermediate slab. This behavior is considered acceptable for the Maximum Design Earthquake because the public life safety is guaranteed.

Taking as a reference the static case, the maximum increment of bending moment acting on the section in correspondence to the central slab during the earthquake is equal to 700 kNm for the operating design earthquake and 1100 kNm for the maximum design earthquake. The results of the analysis indicate a complex response of the system due to particular soil-structure interaction effect and local seismic response phenomena because the soil response is related to the vibration modes excited by the signal. It may be noted that the signals, now taken into account, gives rise to possible soil resonance with the first vibration mode, which leads to increasing shear strains in the deeper soil layers, and, consequently, additional damping according to the strongly nonlinear soil behaviour (Soccodato & Tropeano, 2015).

4 ACKNOWLEDGEMENTS

Partial support received from Salini-Impregilo S.p.A. is acknowledged.

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