

# Use of capacity curve in the seismic analysis of geotechnical systems

*D. Gallese<sup>1</sup>, D. N. Gorini<sup>2</sup>, L. Callisto<sup>2</sup>*

<sup>1</sup> *Ove Arup and Partners, London, UK (formerly Sapienza University of Rome)*

<sup>2</sup> *Sapienza University of Rome, Rome, Italy*

## Abstract

Nonlinear dynamic analysis of soil-structure systems requires advanced and time-consuming computations that may not be feasible for most practical applications. The present research is devoted on conceptualizing and validating simplified procedures that are easier to implement, yet capable of capturing the essential features of the dynamic response of the systems at hand, consistently with modern concepts of seismic performance and capacity design. The geotechnical systems herein considered include retaining structures, bridge abutments, multi-propped excavations, and tunnelling. The seismic capacity of a geotechnical system is studied through nonlinear static numerical analysis (NLSA), in which equivalent inertial forces, proportional to a seismic coefficient, are applied to the system until the activation of a global plastic mechanism. The overall deformability of the system, from static conditions to failure, can be represented by a capacity curve, relating accelerations to seismic displacements of scrutiny points. The capacity curve proves to be a versatile representation of the system response under seismic loading in both displacement-based and equivalent force-based design methods, discussed in the first and second parts of this work. The first part pertains to systems that may accumulate permanent displacements under seismic loading such as earth retaining structures, whereas the second refers to systems that cannot experience important seismic deformations, otherwise, the structural integrity of the entire structure/infrastructure would be compromised. Bridges with integral abutments (IABs) and multi-propped excavations belong to the latter second category. Both methodologies are extensively validated and underscore the essential role of the capacity curve in the seismic assessment of geotechnical systems within the framework of the decoupled approach.

## 1. Introduction

Seismic design of geotechnical systems involves evaluating their performance under earthquake loading, which can significantly differ based on whether the system is able or not to accumulate permanent displacements. Displacing systems, such as slopes, unsupported excavations, and certain retaining structures, exhibit asymmetric behavior under seismic loading. They tend to displace both the soil and structural members towards weaker zones, leading to irreversible deformations. For these systems, a common assumption is that the structural members interacting with the soil do not reach their capacity during strong motions and are therefore regarded as non-dissipative elements. On the contrary, the soil can mobilise its strength, acting as a dissipative element. Conversely, non-displacing systems, such as deep excavations, underground frame structures, and bridge abutments, are characterized by the fact that, if the structural members are designed to remain in the elastic range, these systems cannot accumulate displacements. Therefore, it is logical to expect that the design of the first type of system adheres to the philosophy of the displacement-based approach, while the design of the second type follows the philosophy of the force-based approach.

The distinction between these systems is crucial for selecting appropriate seismic design-methodology. Among the simplified methods to be employed for a practical design, there are the ones based on the decoupled approach, whereas, differently from the advanced and complicated coupled soil-structure interactions systems, the seismic action and system response are evaluated separately and combined only at the end. This design-approach allows for a more manageable assessment of complex systems. In this context, the capacity curve is one of the way to characterise the system response following the modern philosophy of the performance based design.

In summary, identifying whether a geotechnical system is displacing or non-displacing guides the design strategy for controlling seismic performance. Nevertheless regardless of the approach, the capacity curve can be effectively used for both types of systems.

## 2. Methodology and discussion

The seismic capacity of a geotechnical system can be evaluated through NLSA, in which equivalent inertial forces are applied to the system, taken to be proportional to a seismic horizontal coefficient  $k_H$  representing the ratio of the horizontal acceleration to the gravity acceleration. In this context, the capacity curve can be expressed as a relationship between the seismic coefficient  $k_H$  and the corresponding horizontal displacement  $u_R$  of a point of interest, for instance the top of the embedded retaining wall depicted in Figure 1 [1]. In this analysis, commonly known as a ‘incremental pseudostatic analysis’ the seismic coefficient is increased progressively, until the results of the analysis indicate that a plastic mechanism in correspondence of the critical acceleration  $k_C$  is activated.

Due to the nature of displacing systems to accumulate deformations under seismic loading, this curve can be employed in a time-domain calculation to characterise the tangent stiffness, evaluated either on the first loading branch of the curve or along an unloading-reloading cycle (Figure 1b), and the ultimate strength  $k_C$  of an equivalent SDOF system. In the logic of a decoupled approach, the input motion applied to the equivalent SDOF system corresponds to the seismic demand obtained from a free-field one-dimensional ground response analysis at a representative depth of the soil domain. A more detailed and comprehensive picture of this methodology, successfully validated with both numerical analyses and centrifuge tests, is discussed in [1,2,3,4,5].

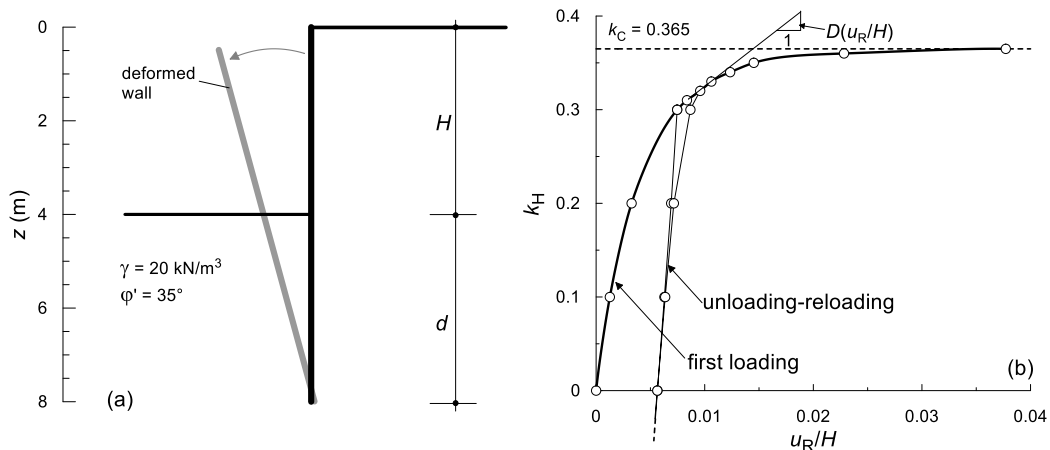


Figure 1. (a) Example embedded retaining wall; (b) non-dimensional capacity curve [1]

In contrast to displacing systems, the seismic design of non-displacing systems generally includes the evaluation of the maximum internal forces in the structural members. Using a single-span integral abutment overpass recently built in Italy as a reference, an advanced coupled 3D soil-bridge model was developed in OpenSees. To facilitate more efficient dynamic computations, a more manageable and validated equivalent 2D model was also created, as detailed in [6,7]. This 2D model serves as a benchmark for validating a simplified procedure to study the seismic behavior of the bridge in the longitudinal direction, which generally governs the overall seismic response.

In IABs, the monolithic connection between the deck and the abutments is such that the seismic response tends to be controlled by the interaction of the abutments with the surrounding soil, and especially with the approach embankments. In the context of the Capacity Spectrum Method (CSM) [8] commonly used for the seismic analysis of civil engineering structures, the capacity curve obtained from a NLSA is combined with a seismic demand, evaluated with a decoupled approach, in the form of an acceleration-displacement (AD) response spectrum. Specifically, the capacity of the system is evaluated through two different distributions of equivalent inertial forces applied, replicating deformation patterns associated with dominant vibration modes. These modes are primarily controlled by the soil response and can be reasonably determined through a modal analysis of the soil deposit including the approach embankment. The entire methodology,

implemented in OpenSees and validated against results of several 3D dynamic analyses conducted on a reference case study is summarized as a flowchart in Figure 2, where only the pattern of  $k_H$  reproducing the first soil-bridge mode is shown for simplicity.

In summary, for practical design, the seismic assessment of geotechnical systems (both ‘displacing’ and ‘not displacing’) can effectively use practice-oriented methods based on the decoupled approach. In this context, the capacity curve, obtained through nonlinear static analysis (NLSA), plays a key role in describing the response of the systems at hand.

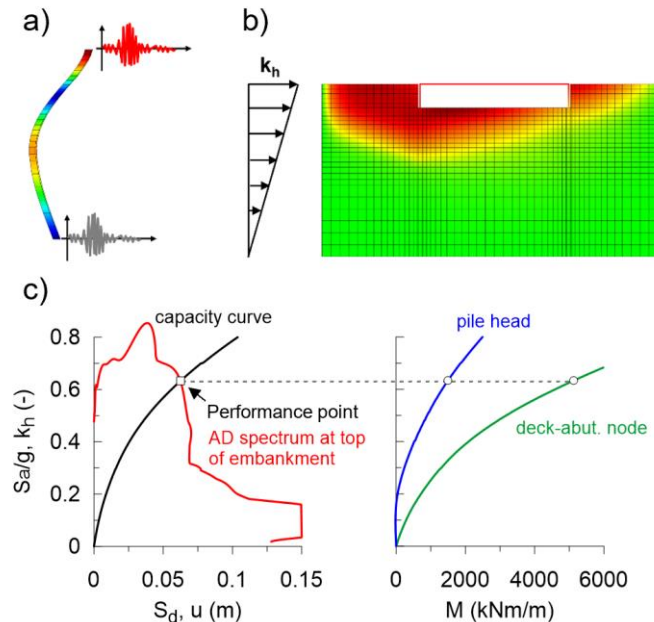


Figure 2. Recap of the simplified tool developed for the seismic design of single-span IAB: a) Free field response used to determine acceleration at the abutment-deck node, b) Nonlinear static analysis applying a seismic coefficient distribution based on the main deformation modes observed from the modal analysis, c) Superimposition of the capacity curve with seismic demand, defining the performance point using the CSM with an iterative procedure for the determination of the equivalent damping.

### 3. References

- [1] Callisto L. (2019). On the seismic design of displacing earth retaining systems. In: Proceedings of the 7th ICEGE. Associazione Geotecnica Italiana, Rome, pp 239–255.
- [2] Callisto L (2014). Capacity design of embedded retaining structures. *Geotechnique* 64:204–214. <https://doi.org/10.1680/geot.13.P.091>
- [3] Laguardia, R., Gallese, D., Gigliotti, R. & Callisto, L. (2020). A nonlinear static approach for the prediction of earthquake-induced deformation of geotechnical systems. *Bull. Earthq. Engng* 18, No. 15, 6607–6627, <https://doi.org/10.1007/s10518-020-00949-2>.
- [4] Callisto L. (2024). A method for the seismic design of multi-propped retaining walls. *Italian Geotechnical Journal* (1), 2024. [dx.doi.org/10.19199/2024.1.0557-1405.044](https://doi.org/10.19199/2024.1.0557-1405.044).
- [5] Gallese D., Callisto L. (2024). A simple tool for the capacity curve of embedded retaining systems – part I and part II. *Ground Engineering*, July and August/September issue. <https://www.geplus.co.uk/>
- [6] Gallese, D. (2022). Soil–structure interaction for the seismic design of integral abutment bridges: from advanced numerical modelling to simplified procedures. PhD thesis, Sapienza University of Rome. See <https://hdl.handle.net/11573/1666837>.
- [7] Gallese D., Gorini D.N., Callisto L. (2023). A nonlinear static analysis for the seismic design of single-span integral abutment bridges. *Gèotechnique*. <https://doi.org/10.1680/jgeot.22.00229>
- [8] Freeman, S.A., Nicoletti, J.P., Tyrell, J.V.: Evaluations of existing buildings for seismic risk a case study of Puget sound naval shipyard, Bremerton, Washington. In: Proceedings of the 1st US National conference on earthquake engineering. Berkeley, USA (1975)