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СТЕПГРАД

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SEISMIC EVALUATION OF A SIX STOREY FRAME STRUCTURE CONSIDERING SOIL EARTHQUAKE RECORDS FROM BALKAN REGION

Abstract:

This study emphasizes numerical modeling of soil medium including boundary conditions, rather than the conventional focus on input earthquake accelerations with simplified Winkler soil models typically used in soil-structure interaction (SSI) problems. A six-story frame structure founded on relatively soft ground is numerically simulated in ANSYS using user-defined elements, with the soil medium modeled according to Eurocode 8 and boundaries represented by infinite elements to prevent outward wave propagation. The analysis considers different earthquake scenarios from the Balkan Peninsula (Montenegro, Albania, and North Macedonia) that vary in magnitude and frequency, incorporating nonlinear soil behavior to evaluate how combined soil conditions and seismic input simultaneously affect structural performance.

Keywords: soil-structure interaction, frame structure, seismic evaluation, numerical modeling, Eurocode 8,

СЕИЗМИЧКА ОЦЈЕНА ШЕСТОСПРАТНЕ ОКВИРНЕ КОНСТРУКЦИЈЕ УЗИМАЈУЋИ У ОБЗИР ЗЕМЉОТРЕСНЕ ЗАПИСЕ ИЗ РЕГИОНА БАЛКАНА

Сажетак:

Ово истраживање ставља акценат на нумеричко моделирање тла и одговарајућих граничних услова, за разлику од уобичајеног приступа у анализама интеракције тло–конструкција, који се најчешће заснива на анализи улазних сеизмичких убрзања уз примјену поједностављених Винклерових модела тла. Шестоспратна оквирна конструкција темељена на релативно меком тлу нумерички је симулисана у програмском пакету ANSYS коришћењем кориснички дефинисаних елемената. Модел тла формиран је у складу са одредбама стандарда Еврокод 8, док су граничне зоне домена представљене бесконачним елементима са циљем спречавања одбијања и вјештачког ширења сеизмичких таласа ка спољашњости модела. У анализи су разматрани различити сценарији земљотреса са подручја Балканског полуострва (Црна Гора, Албанија и Сјеверна Македонија), који се међусобно разликују по магнитуди и фреквенцијском садржају. При томе је у модел укључено нелинеарно понашање тла како би се испитао комбиновани утицај карактеристика тла и улазне сеизмичке побуде на одговор конструкције.

Кључне речи: интеракција тла и конструкције, рамовска конструкција, сеизмичка евалуација, нумеричко моделирање, Еврокод 8

1. INTRODUCTION

Recent decades have witnessed significant advancements in software capabilities for numerical simulation of frame structures, where earthquake input is considered as time-dependent acceleration. Simulating soil-structure interaction problems requires the simultaneous consideration of both soil and structure, which can be time-consuming and needs attention. Moreover, in numerical simulation of soil medium as a wide region the boundaries should be given special concern to prevent the results by reflection of the traveling waves in the soil medium. In dynamic analysis the situation is additionally complicated by the inertia terms such the radiation of the wave should be considered. The problems in soil structure interaction arise when computing the structural response to seismic response especially when tall buildings are supported [1]. Site-specific recorded ground motions, which are reasonably representative of the projected seismic hazard, are often unavailable for most locations. Additionally, engineers understand that, due to the stochastic nature of earthquake ground motion, the information obtained from a structural response analysis using a single record is highly unreliable [2], potentially misrepresenting both the magnitude and distribution of structural demands. The inclusion of the soil structure interaction effects influences the results considerably. Recent publications have focused on assessing the safety of massive structures when subjected to seismic forces. The behavior of large structures founded on relatively soft ground in dynamic scenarios can be significantly affected by both soil-structure interaction and the characteristics of the applied excitation loads.

2. SOIL STRUCTURE INTERACTION

In order to accurately model the soil medium in soil-structure interaction problems, either the finite element region should be sufficiently widened to prevent reflection of seismic waves from the boundaries, or special boundary conditions should be employed to absorb the waves at the boundaries. The influence of the soil medium in the response of SSI system has been considered analysing different earthquake data from the Balkan Region. The soil medium is considered to be of medium dense sandy material which can be presented as a B type of soil according to Eurocode 8 classification. Table 1 presents the soil layer properties, where deeper layers are characterized by enhanced shear strength and stiffness:

Table 1. Soil layers properties

Number of layer	Thickness (m)	Unit weight (kN/m^3)	Shear Velocity in soil medium (m/s)
1	8	16	330
2	10	17	420
3	12	18	510

The soil layer properties have been varied for a three-layer ground profile with a total depth of 30m. The layer geometry is presented in Figure 1 below. The soil material behavior is modeled using the Drucker-Prager constitutive model as implemented in ANSYS software.

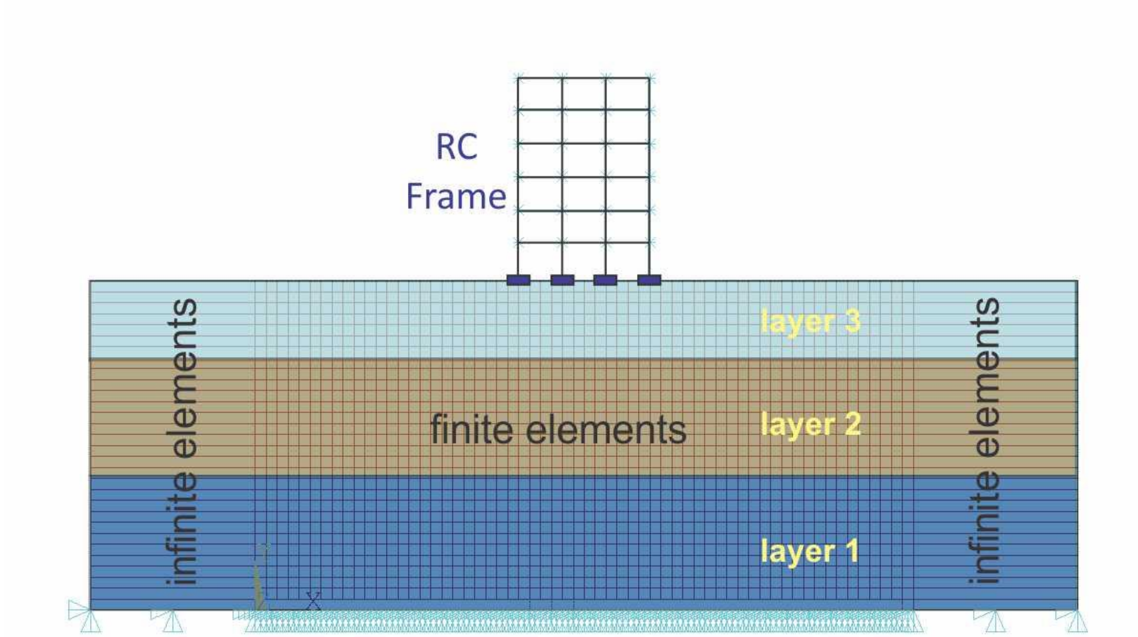

Figure 10. Numerical model of SSI (figure created by author)

In this direct time-domain method, the soil medium is modelled using two-dimensional quadrilateral elements with the finite element method. Similar soil-structure interaction problems have been studied by other authors [3], [4]. To provide a complete representation, the soil side boundaries are simulated as a domain composed of finite elements bounded by infinite element boundaries.

The six storey frame structural elements are idealized as two-dimensional elastic beam elements having three degrees of freedom at each node: translations in the nodal x and y directions and rotation about the nodal z axis. The frame structure is assumed to behave elastically and has been modelled using two parameters: the modulus of elasticity $E = 3.15\times10^7$ kPa and Poisson's ratio $\nu = 0.2$. The bay length of the frame is 4.0 m, while the storey height is 3.0 m. The beam cross-section is 40 × 50 cm and the column cross-section is 50 × 50 cm. A mass of 11 tons is assigned to each node to simulate realistic structural behavior (a total of 44 tons per floor). The structure is modelled as a six-storey RC frame, and the soil medium is represented as a two-dimensional model composed of three layers resting on bedrock.

The dynamic analysis has been performed using transient analysis with the step-by-step method. The proportional viscous damping matrix is taken to be proportional to both mass and stiffness matrices (Rayleigh damping). Finite element modelling of the coupled soil-structure system is performed using ANSYS software. The effect of soil-structure interaction is evaluated using acceleration time histories of different earthquakes scaled to a peak ground acceleration of 0.25 g. Modal analysis of the coupled soil-structure system yields a fundamental period of 0.5 s, which plays an important role in defining the overall response of the structure resting on the soil layers.

2.1. DETERMINATION OF SEISMIC ACTION

Dynamic response of a structure supported on flexible soil may differ significantly from the response of the same structure when having a rigid base [5]. As given in the work of many authors, the spatial variability of ground motion includes wave passage effects which influence the ground motion at the intersection with the structure founded on top the soil. A time-domain analysis is performed to capture the modifications in earthquake time histories, incorporating both recorded strong motion accelerograms and an artificial earthquake generated in accordance with EC8 soil type B requirements. The availability of earthquake information is an important component in seismic analysis of structures. As given in Eurocode 8, the excitations should be preferably consisting of accelerograms recorded on soil sites in real earthquakes as they possess realistic low frequency content. The location for which the analysis has been done is in Skopje, capital of Macedonia for which according to geotechnical analysis soil type of B is chosen according to Eurocode 8 soil classification. The earthquakes which have been selected are the earthquakes from surrounding locations in coordination with the Seismic zoning map for return period of 475 year [6].

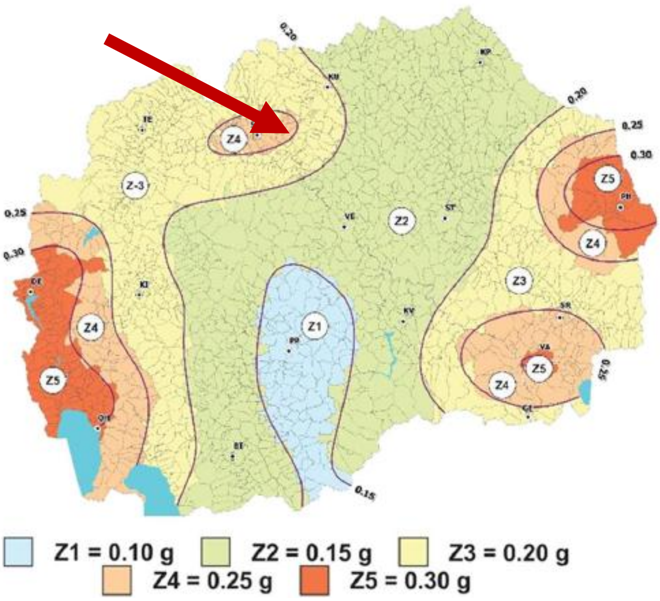

Figure 11. Location of this study in the map (created by author).

Figure 2 indicates that the Skopje region is characterized by a peak ground acceleration of 0.25 g. Consequently, all selected earthquake time histories have been scaled to this value. The acceleration spectra of the selected earthquakes are presented in Figure 3, together with the EC8 Type 1 for soil tye B soil spectrum for comparison

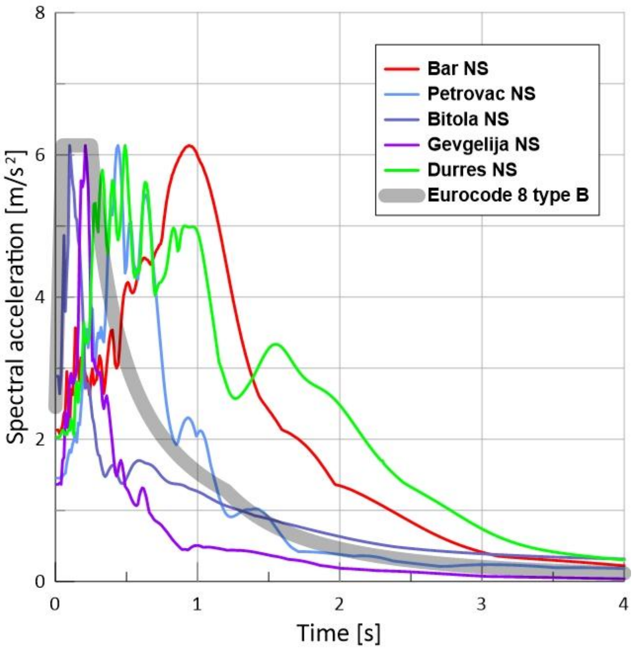

Figure 12. *Comparison of return spectra from earthquakes including EC8 type 1 for soil type B (created by author).*

Figure 3 shows that the Bitola NS and Gevgelija NS ground motions have pronounced short-period spectral peaks, while the Bar NS motion peaks at 0.8-1.2 seconds. This demonstrates the diverse frequency content among the selected earthquakes, which significantly influences structural response. When comparing the natural period of the structure resting on top of soil which is 0.5sec as given above, it can be predicted that the Eurocode spectrum has an acceptable weight in the overall structural response. In order to simulate EC8 spectrum in time domain three artificial earthquake time histories have been generated and labelled as Gen.Eq1-3. In Figure 4 it can be seen that the spectra of generated earthquakes have very little deviances (less than 5%) from the original spectrum suggested by Eurocode 8 for type 1 for B soil type.

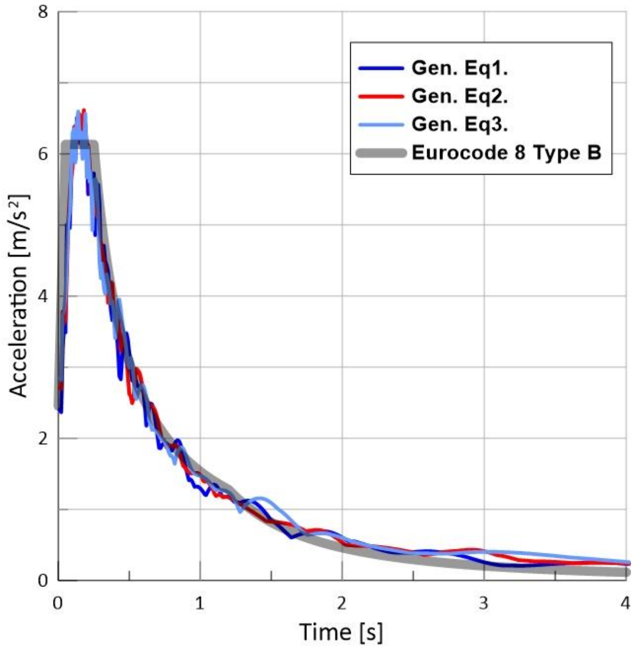

Figure 13. Comparison of return spectra from earthquakes including EC8 type B (created by author).

The synthetic time history Gen.Eq. 1 serves as the representative record for the EC8 Type B spectrum. Real acceleration time histories from the Balkan region, classified by source country, include:

From North Macedonia:

- Bitola N-S (01.09.1994, M=5.2 - 5.4)
- Gevgelija N-S (21.12.1990, M=5.6) from the Griva, Greece earthquake

From Montenegro (15.04.1979, M=7.0):

- Bar N-S: selected for its broad frequency content
- Petrovac N-S: selected for dominant periods of 0.25 - 0.5 s

From Albania:

- Durres N-S (26.11.2019, M=6.4)

Figure 5 shows the acceleration time histories for all selected records.

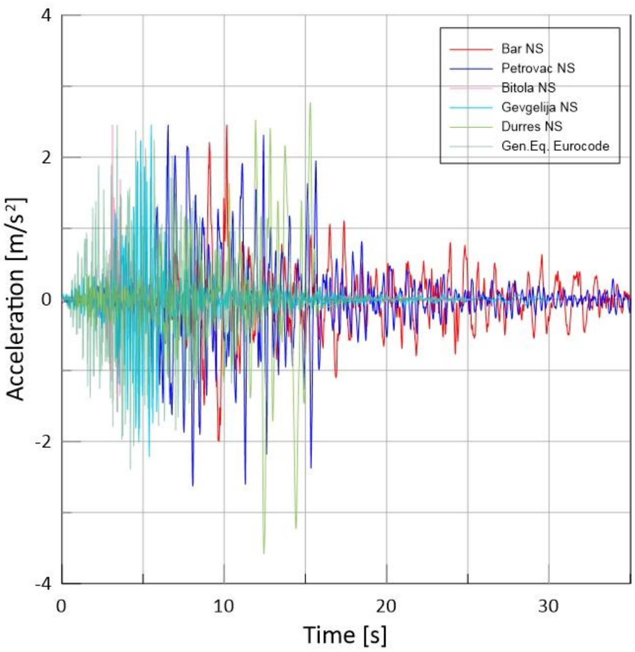

Figure 14. Acceleration time histories of input earthquakes (created by author).

All earthquake signals in this work have been baseline corrected by using own routines in MATLAB software corresponding to the work of Tian et.al (Tian et al., 2019). Next, the example of the Durres earthquake baseline correction is shown (Figure 6).

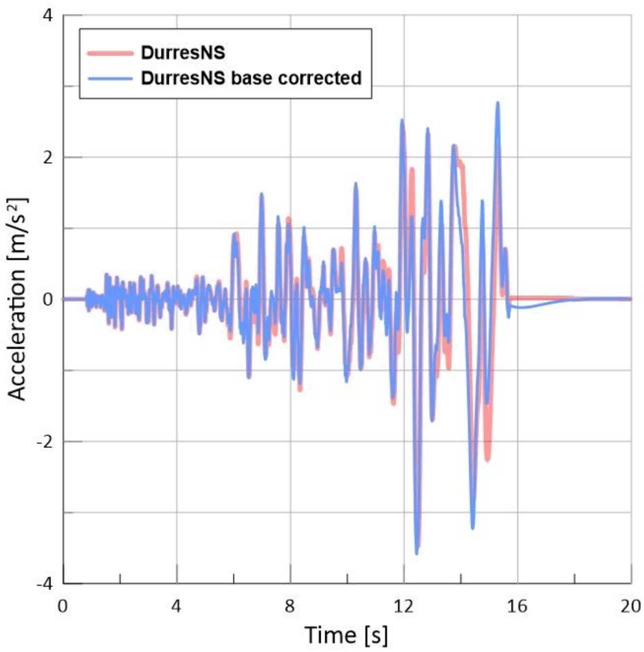

Figure 15. Base corrected acceleration time history of DurresNS earthquake (created by author).

After having established the earthquake time histories and soil layer properties, the next critical aspect is the proper treatment of domain boundaries. Section 3 presents the infinite element formulation employed to absorb outward-propagating waves at the boundaries.

3. INFINITE ELEMENTS

The boundary conditions which represent important step in simulation of soil medium has to be considered carefully. The formulation of infinite elements follows the same fundamental principles as conventional finite elements, with the additional requirement of an appropriate mapping that allows the computational domain to extend to infinity. Infinite elements are first developed by Zienkiewicz et al. [8] and since then have been developed in frequency and time domain. In the work of Häggblad et al. [9] infinite elements with absorbing properties have been proposed which can be used in time domain. In the work of Sesov [10] and Edip [11] the infinite elements have been introduced by six nodes and ability to consider bilinear effects at the boundaries. In this work the development of infinite element has followed the techniques considering the time domain in which the infinite element is obtained from a six nodded finite element as shown in Fig 7.

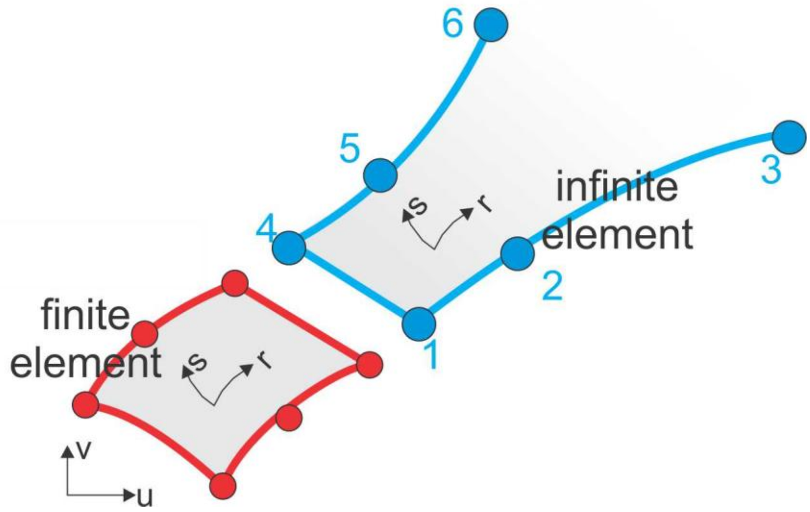

Figure 16. Nodes coupling of finite and infinite elements (created by author).

The element displacement in *u* and *v* direction is interpolated with the usual shape functions N^1, N^2, $N^4$and N^5:

$$u = [N_1 \quad N_2 \quad 0 \quad N_4 \quad N_5 \quad 0]\mathbf{u}$$
$$v = [N_1 \quad N_2 \quad 0 \quad N_4 \quad N_5 \quad 0]\mathbf{v} \tag{1}$$

In expression (1), **u** and **v** are vectors with nodal point displacements in global coordinates. The shape functions are given in expression (2) as:

$$N_1 = -(1-s)r(1-r)/4$$
$$N_2 = (1-s)(1-r^2)/2$$
$$N_4 = -(1+s)r(1-r)/4$$
$$N_5 = (1+s)(1-r^2)/2 \tag{2}$$

Based on the isoparametric concept, the infinite element in global coordinate is mapped onto an element in local coordinate system using the expression in (3). In the formulation of the infinite element, only the positive *r* direction extends to infinity.

$$r = [M_1 \quad M_2 \quad 0 \quad M_4 \quad M_5 \quad 0]\mathbf{r}$$
$$s = [N_1 \quad N_2 \quad 0 \quad N_4 \quad M_5 \quad 0]\mathbf{s} \tag{3}$$

The number and location of the nodal arrangement at the finite-infinite element interface must be identical to ensure displacement continuity. The key advantage of the proposed infinite elements is their compatibility with standard finite elements used in numerical analyses, enabling proper transfer of internal forces across the boundary. Figure 8 presents the vertical stress distribution at t=3 seconds during the Petrovac NS earthquake.

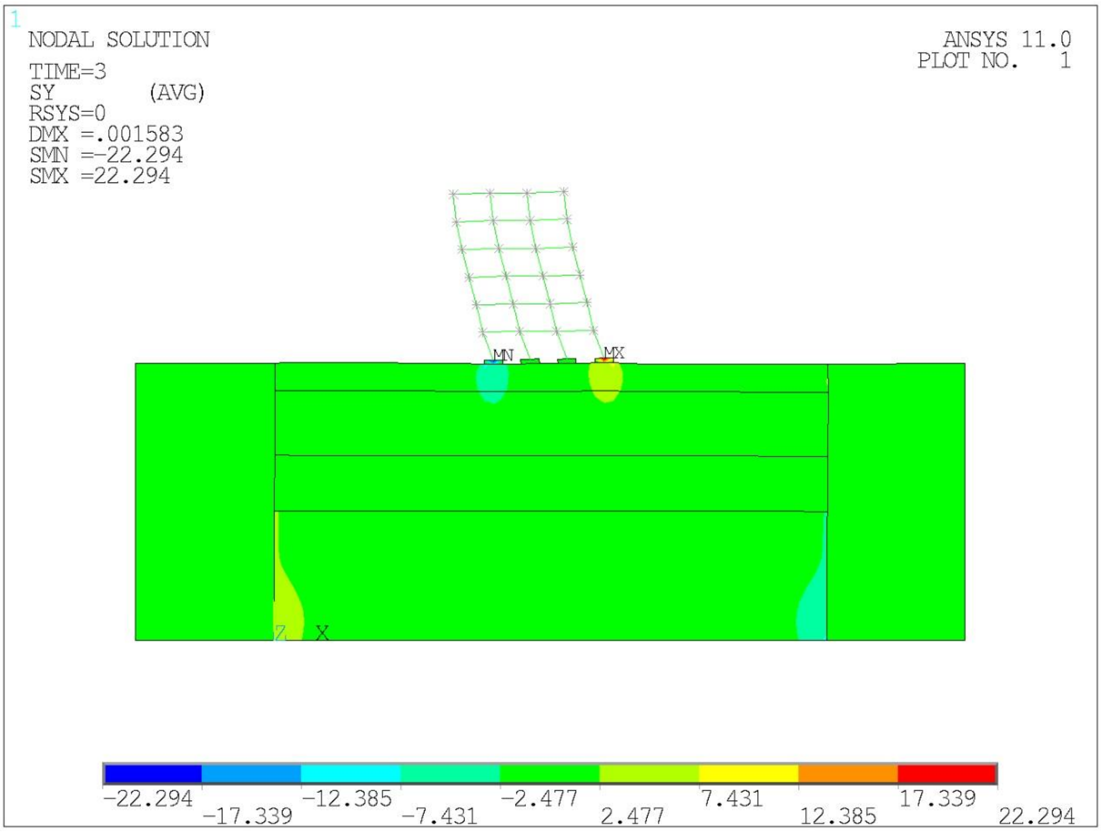

Figure 17. Vertical stress values at time=3second of Petrovac NS earthquake time history (created by author).

As shown in Figure 8, the stress fields at the coupling interface below the structure are consistent with the anticipated tension and compression zones. Additionally, the finite-infinite element coupling facilitates absorption at the boundaries, confirming the validity of the numerical results.

4. RESULTS COMPARISON

The performance of structural systems is typically assessed in terms of the maximum response, which is then compared to an allowable response value associated with damage or failure. In order to get a better insight of the structural response acceleration values at the bottom of the structure have been compared in order to consider the effects of soil amplification of the ground motions. The acceleration values show that the increase is mostly seen in the earthquake records of Petrovac NS and Durres NS cases in which the acceleration values have been increased more than two times. On the other hand, the effects of earthquakes of Bitola NS and Bar NS the increase is more than once of the input acceleration. The results obtained by EC8 generated earthquake have the average values which play an important role in design considerations although for structures with great importance, real set of occurred earthquakes from the local region should be considered.

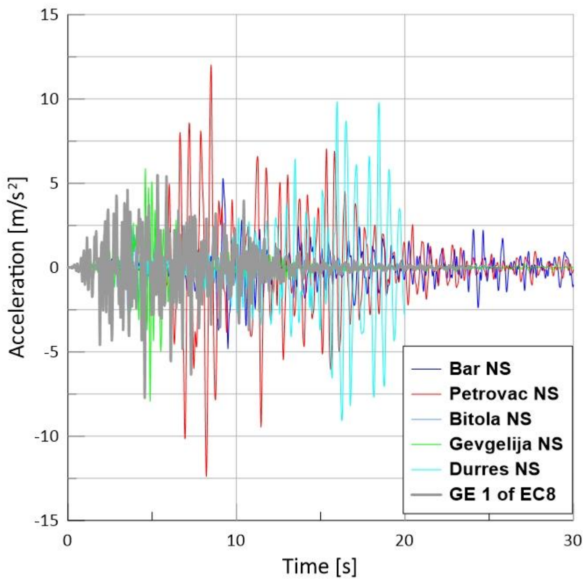

Figure 18. Acceleration time history at the bottom of the structure (created by author).

In comparing the horizontal displacement, it is clearly seen that the records of Petrovac NS and Durres NS have the biggest values. The seismic excitation encountered by the structure is a function of various factors, including the earthquake source, local site effects, traveling path and the SSI effects. In particular, the acceleration within structure are affected by the flexibility of the foundation system [12]. In this case considering the fact that infinite elements absorb the waves the traveling path effects are minimized. However, the effects of local site effects and the SSI effects are of primary importance in amplification of the results. As can be seen from Figure 10 the values of displacement are greater in the case of Petrovac NS and Durres NS earthquake time histories. The maximum displacements are very sensitive to base-correction criteria applied to accelerograms also. The values obtained from generated earthquake of Eurocode 8 spectrum are in the average range which shows the importance using Eurocode generated ground motions in this type of analysis when structures of high importance are considered.

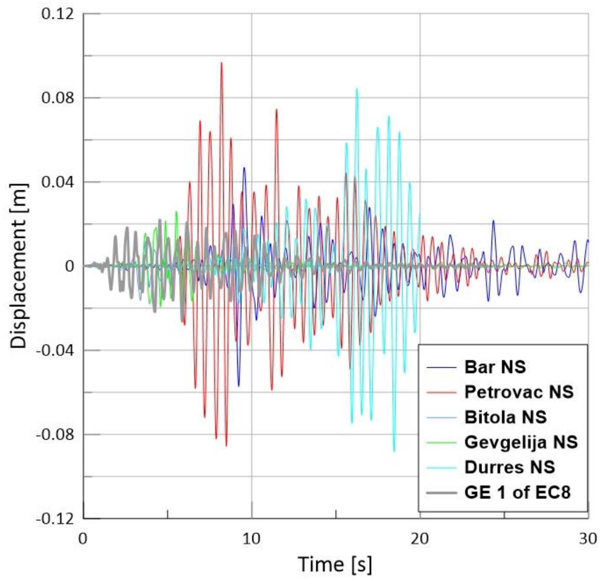

Figure 19. Displacement time history at the top of the structure (created by author).

The structural moment time history which is obtained from the frame structure at the top right node is shown in Figure 11 which shows similar trends to displacement. The Petrovac NS earthquake produces the maximum positive moment of approximately 195 kNm, while the Durres NS record generates the largest negative moment of about -180 kNm. The synthetic EC8 earthquake maintains moment demands within a moderate range, consistent with its design spectrum characteristics.

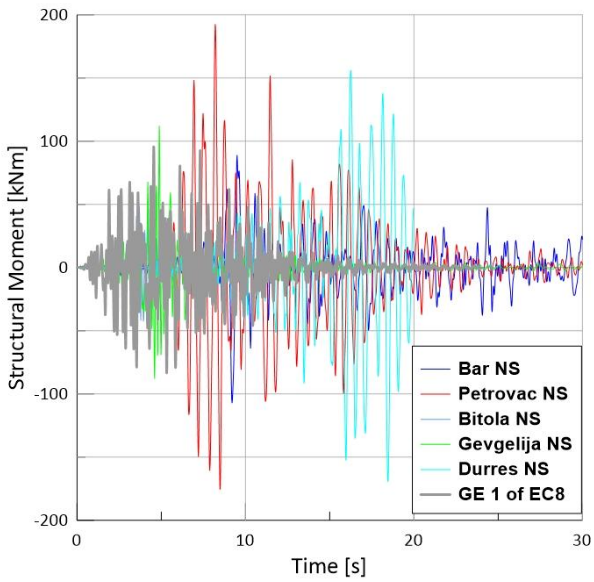

Figure 20. Structural moment time history at the top of the structure (created by author).

These results highlight the critical role of earthquake frequency content in determining structural response, as records with similar peak ground accelerations can produce substantially different internal force distributions. The coupling between soil properties and seismic input characteristics emerges as a dominant factor governing the overall structural behavior in soil-structure interaction systems.

5. CONCLUSIONS

This study successfully implemented a coupled finite-infinite element model in ANSYS to analyze soil-structure interaction (SSI) for a six-story frame on soft soil using scaled Balkan earthquake records (PGA=0.25g) and synthetic EC8 motions, revealing the fundamental period shift to 0.5s and nonlinear soil effects via Drucker-Prager criteria. Results demonstrate significant SSI amplification as :

- ground-level accelerations doubled in Petrovac NS and Durres NS cases, versus milder increases in Bitola NS and Bar NS;
- top displacements and structural moments peaked at Petrovac NS exceeding EC8 synthetic time history underscoring frequency content's role over PGA alone in soft soil scenarios.

For high-importance structures in the Balkans, seismic designs should prioritize using region-specific earthquake records from local events alongside Eurocode 8 spectra. This combined approach captures frequency-specific amplifications and soil-structure interaction effects not fully represented by synthetic motions alone. Relying solely on EC8 spectra might underestimate the structural demands as demonstrated by the Petrovac NS and Durres NS records in this study.

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