# Efficiency of Transmitting Boundaries on Dynamic Response of Soil-Structure Interaction Systems

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## ABSTRACT

In this study, efficiency of transmitting boundaries which is one of the local procedures is investigated for dynamic analysis of the soil-structure interaction systems and the results are compared with traditional boundaries. Sarıyar concrete gravity dam is chosen for an application. For the soil-structure interaction system of the chosen dam, two different finite element models are prepared. In the first model, the infinite soil media on which the dam has been built is classically represented with finite size using traditional boundaries. In the second model, the infinite soil region is represented with finite size using transmitting boundaries. Dynamic analysis of these soil-structure interaction systems are performed with a computer program for approximate 3-D analysis of soil-structure interaction problems (FLUSH). As a result of the analyses, spectrums of acceleration, velocity and displacement are obtained for crest point of the dam.

## INTRODUCTION

A complete analysis of the soil-structure interaction problem must involve a determination of the response of a structure when it is subjected to earthquake ground motions which vary from point to point in the soil and rock around and underlying the structure and travel in some unknown way across the base structure [1]. On the basis of this approximation, a good estimation of the response of the structure under the dynamic effects is required to choosing of the appropriate mathematical model. The most common model is generally traditional finite element model [2].

The finite element method which can be apply with many idealization for soil and structure represents infinite soil media as a finite and bounded media. The encountered numerical problem in dynamic soil-structure interaction analysis with the method is how to simulate waves that radiate outward from the excited structures towards infinity. The dynamic response of massive structures such as nuclear power plants and dams may be influenced by the soil-structure interaction as well as the dynamic characteristics of the exciting loads and the structures [3]. To model the infinite soil media, a radiation condition at infinity has to be satisfied.

Various boundary conditions are developed by researchers for soil-structure interaction systems. Lysmer and Kuhlemeyer [4] developed viscous boundaries which represent dashpots that absorb P-waves and S-waves. Richart et al. [5] and Graff [6] developed transmitting boundaries which absorbs wave effects emanating from the structure and thus simulate the effects of an extensive soil deposit. Clayton and Engquist [7] presented paraxial boundaries, Brebbia et al. [8] presented the well known boundary element method, Berenger [9] presented perfectly matched layer which is a refined and promising absorbing layer, Song and Wolf [10] developed the scaled boundary finite-element method, a novel semi-analytical technique. Wolf and Song [11] formulated a doubly asiymptotic multi-directional boundary, Tsynkov [12] developed exact non-reflecting boundary conditions which are constructed by analytical solution for unbounded domains of simple geometry and material property, Astley [13] developed infinite elements based on the finite-element technology to absorb outgoing waves to infinity. The results from all studies indicates that the wave propagation in the infinite media can be obtained and infinite soil media can be idealized by these boundary conditions and modeling methods.

In this study, efficiency of transmitting boundaries proposed by Lysmer et al. [1] is investigated for dynamic analysis of the soil-structure interaction systems and the results are compared with those of traditional boundaries.

## EQUATION OF MOTION

The equation of motion for a finite element representation of soil-structure interaction system is given by Lysmer et al. [1]

$$[M]\{\ddot{u}\}+[K]\{u\}=-\{m\}\ddot{y}+\{F\}-\{T\} \tag{1}$$

where $\{u\}$ are the displacements of the nodal points relative to the rigid base, $[M]$ and $[K]$ are mass and stiffness matrices of the system, respectively, and $\{m\}$ is a vector related to mass matrix and direction of rigid base acceleration, $\ddot{y}$ (t). Material damping can be included by forming $[K]$ from complex moduli.

The forces $\{F\}$ are the static vertical forces acting on the both ends of the slice. These forces develop due to the difference of the total displacement at the nodal points. These are defined as

$$\{F\}=[G]\,\{u\}_f \tag{2}$$

where $[G]$, $\{u\}_f$ are the stiffness matrix formed from complex modulus of the free-field and free-field displacements, respectively. The forces related to the energy transmission are:

$$\{T\} = \left([R]+[L]\right)\left(\{u\}-\{u\}_f\right) \quad (3)$$

where $[R]$ and $[L]$ are the frequency-dependent boundary stiffness matrices which represent the exact dynamic effect of the semi-infinite viscoelastic soil system. The equation of motion can be solved by the complex response method which assumes that the input motion can be written as a finite sum of harmonics, i.e. a truncated Fourier series:

$$\ddot{y}(t) = \mathrm{Re}\sum_{s=0}^{N/2} \ddot{y}_s \exp(i\omega_s t) \quad (4)$$

$$\{u\} = \mathrm{Re}\sum_{s=0}^{N/2} \{u\}_s \exp(i\omega_s t) \quad (5)$$

$$\{u\}_f = \mathrm{Re}\sum_{s=0}^{N/2} \{u_f\}_s \exp(i\omega_s t) \quad (6)$$

where N is the number of digitized points in the input motions. The amplitudes $\ddot{y}(t)$ and $\{u_f\}_s$ can be found easily by the Fast Fourier Transform algorithm.

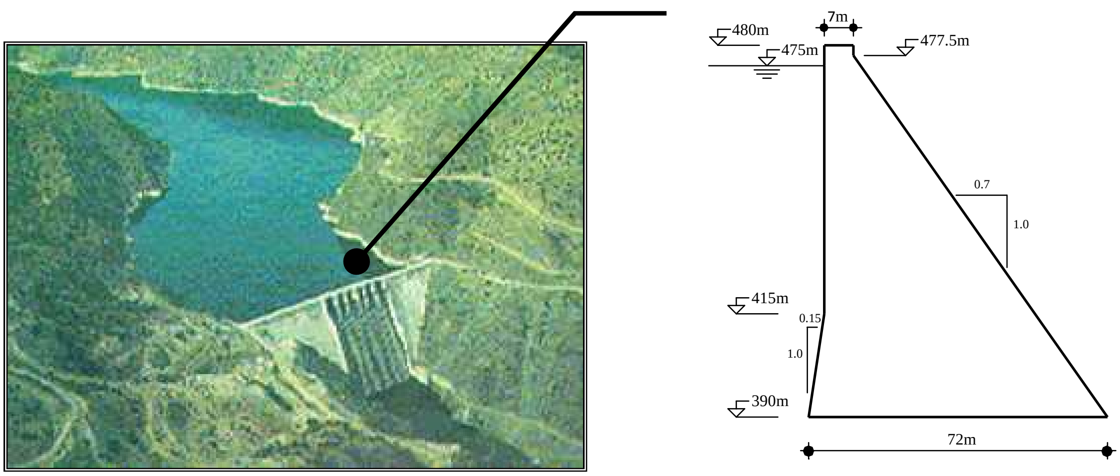
$$\begin{aligned}&\left([K]+[R]_s+[L]_s+\frac{i\omega_s}{L}[C]-\omega_s^2[M]\right)\{u\}_s = \\ &-\{m\}\ddot{y}_s+\left([G]+[R]_s+[L]_s+\frac{i\omega_s}{L}[C]\right)\{u_f\}_s\end{aligned} \quad (7)$$

which is a set of linear equations which determines the displacement amplitudes $\{u\}_s$ at the each frequency $\omega_s$, s=0, 1,…,N/2. The equations can be solved by Gaussian elimination and the displacements in the time domain follow from eq. (5) by the inverse Fast Fourier Transform. $[C]$ is a simple diagonal matrix which depends on the properties of the free field.

## NUMERICAL APPLICATION

Sarıyar concrete gravity dam (Figure 1a) is chosen in order to investigate efficiency of transmitting boundaries on dynamic response of the soil-structure interaction systems. Sarıyar dam on the Sakarya River is 120km to the northeast of Ankara, the capital of Turkey. The main purpose of the dam is to supply electric power. It has a crest length of 257m. The crest width is 7m. Maximum reservoir height of the dam is 85m. The dimensions of the dam are given in Figure 1b.

The finite element model of the dam-foundation coupled system prepared by using traditional boundaries is given in Figure 2, and that using transmitting boundaries is given in Figure 3. In the dam-foundation coupled model with traditional boundaries (Figure 2), all the bottom boundary nodes of the foundation domain are provided with rollers allowing only horizontal movements whereas the both side boundary nodes are fully fixed. Transmitting boundaries absorb any wave effect emanating from the structure due to the surface Rayleigh waves [1]. These boundaries also help to simulate the effects of an extensive soil deposit which is assumed to be layered. Soil volumes for the dam-foundation coupled system may be reduced when finite element model is provided with transmitting boundaries at the side boundary nodes of the foundation domain (Figure 3).




**b)** Cross-section of Sarıyar dam

**a)** A view of Sarıyar dam

Figure 1. A view and cross-section of Sarıyar concrete gravity dam

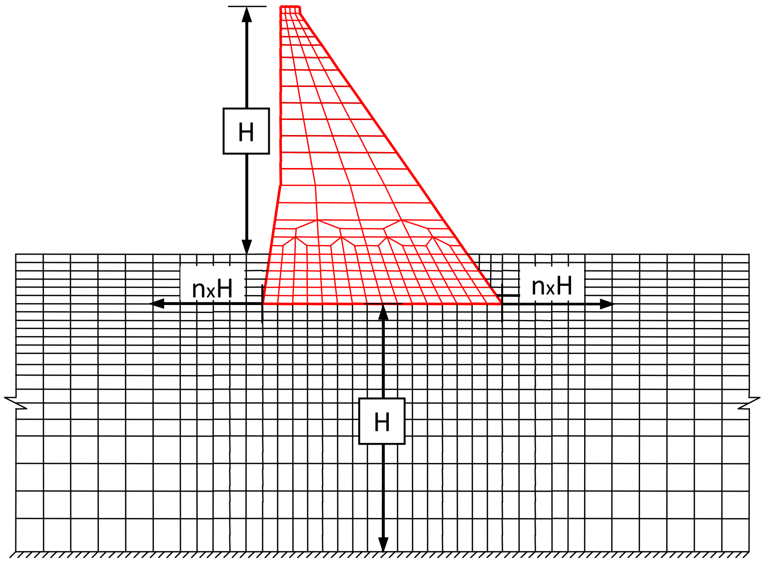



Figure 2. The finite element model of the dam-foundation coupled system prepared by using *traditional boundaries*

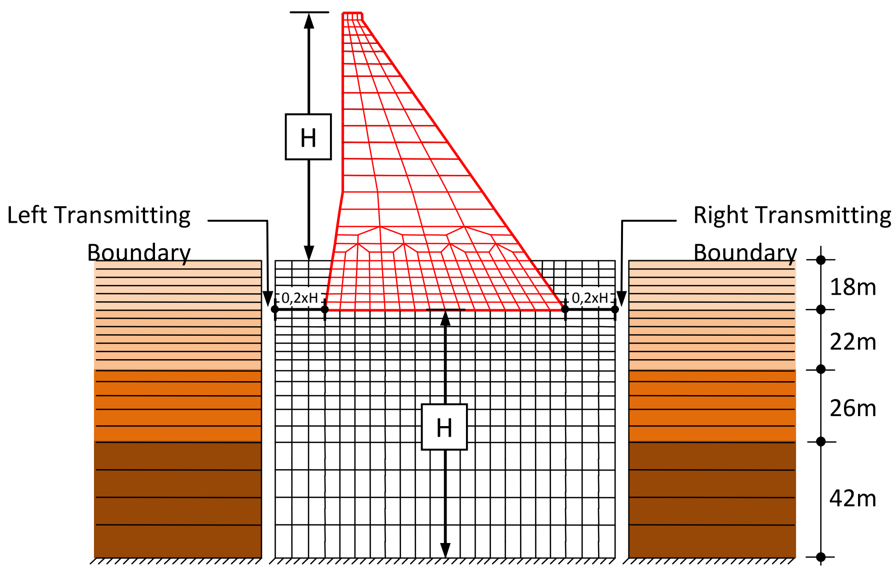



Figure 3. The finite element model of the dam-foundation coupled system prepared by using *transmitting boundaries*

Dam body and foundation was represented by 4-noded displacement-compatible isoparametric quadrilateral elements in the dam-foundation coupled model with both traditional boundaries and transmitting boundaries. The plane strain assumption was employed in the analysis. The material properties of the soil-structure interaction system for this study are as follows: elasticity modulus, unit weight and Poisson's ratio of the dam concrete are taken as $35x10^9 N/m^2$, 24000 $N/m^3$, and 0,15, respectively. Elasticity modulus, unit weight and Poisson's ratio of the soil profile change from soil surface to rigid base and are given in Figure 4. The complex response method is used for the solution and the materials with strain-independent are chosen in this study. Damping ratio of the system is chosen as 5%. Water height in reservoir is 85m. The effects of hydrodynamic pressures occurred due to the earthquake are taken consideration with Westergaard approach.

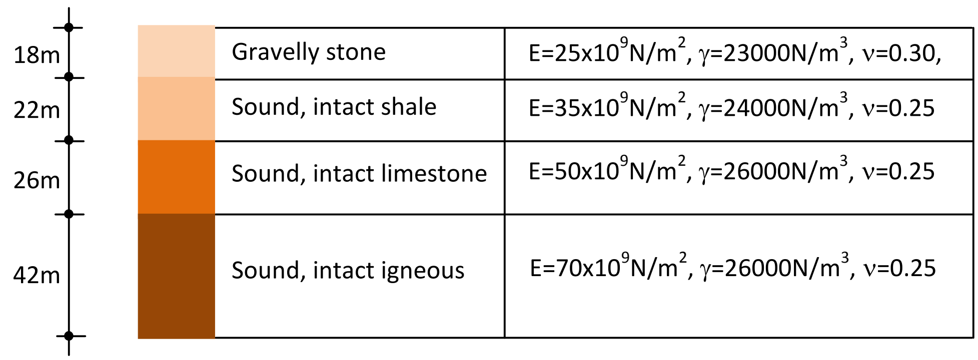
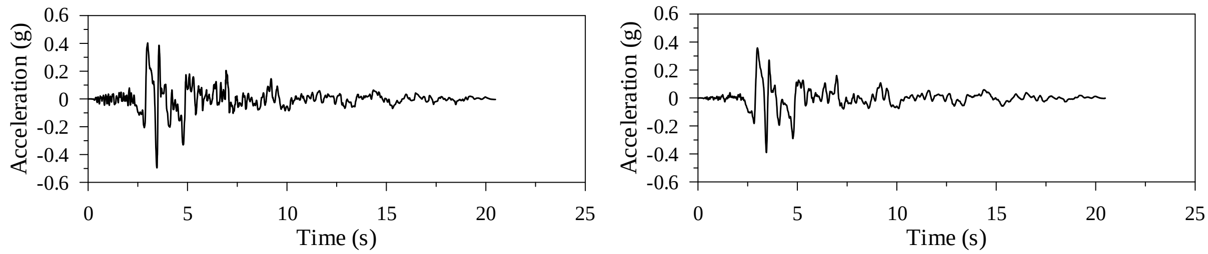



Figure 4. Soil profile and mechanical properties

The E-W component of the Erzincan Earthquake, March 13, 1992, Erzincan, Turkey is chosen as free-field motion and given in Figure 5a. Since rigid base motion is effective on the dynamic response of soil-structure interaction systems, the free-field motion is deconvolved for soil layers according to one-dimensional wave propagation. The rigid base motion obtained from deconvolution is given Figure 5b.




**a)** The free-field ground acceleration **b)** The deconvolved ground acceleration

Figure 5. The time-history of the free field and deconvolved ground acceleration for The E-W component of the Erzincan Earthquake, March 13, 1992, Erzincan, Turkey

In the soil-structure interaction system, the size of a foundation model should be selected so that dam responses are accurately computed. In this study, *firstly* the size of foundation model considered in FLUSH is controlled by taking into consideration five different soil volumes for the dam-foundation coupled system with traditional boundaries. The depth of the foundation models is assumed as constant and is 1H distance from dam base. The sizes of foundation models are considered as 1H, 2H, 3H, 4H and 5H distance from dam body in longitudinal direction. Response spectrums at the dam crest for five different size of foundation model with traditional boundaries are presented in Figure 6. It is shown from the figure that the crest response does not change for 4H-5H foundation size. Therefore, the size of foundation is selected as 5H distance from dam body in longitudinal direction for the dynamic analysis of the dam-foundation coupled system of the dam with traditional boundaries.

*Secondly*, in the finite element model of the dam-foundation coupled system prepared by using transmitting boundaries, the size of foundation is considered as 0,2H distance from dam body in longitudinal direction and transmitting boundaries are used on two sides of model (Figure 3). Response spectrums at the dam crest for two different foundation model using traditional boundary with 5H foundation size and transmitting boundaries are presented in Figure 7. It is shown from the figure that the crest acceleration and crest response is approximately same for two models.

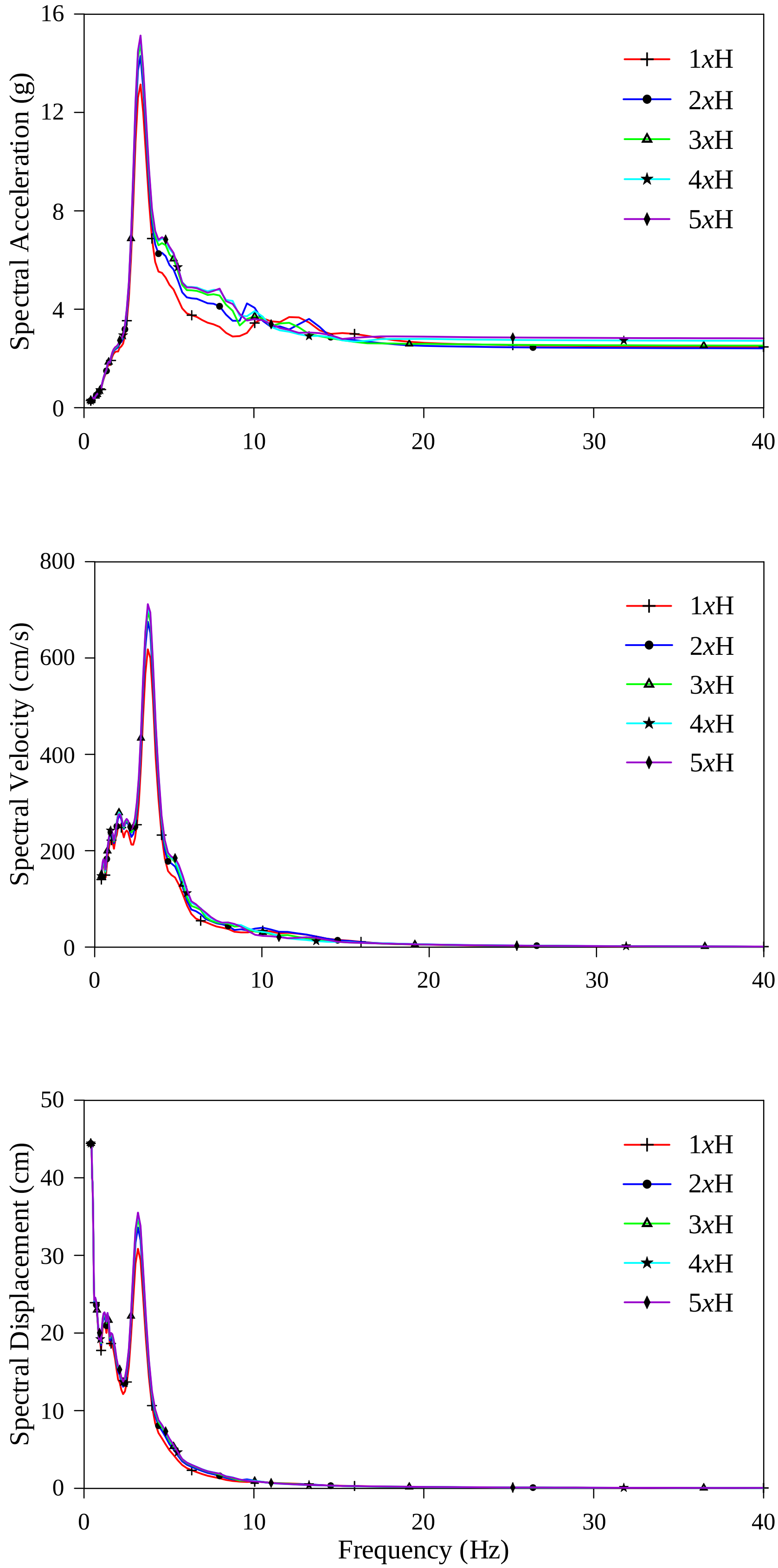
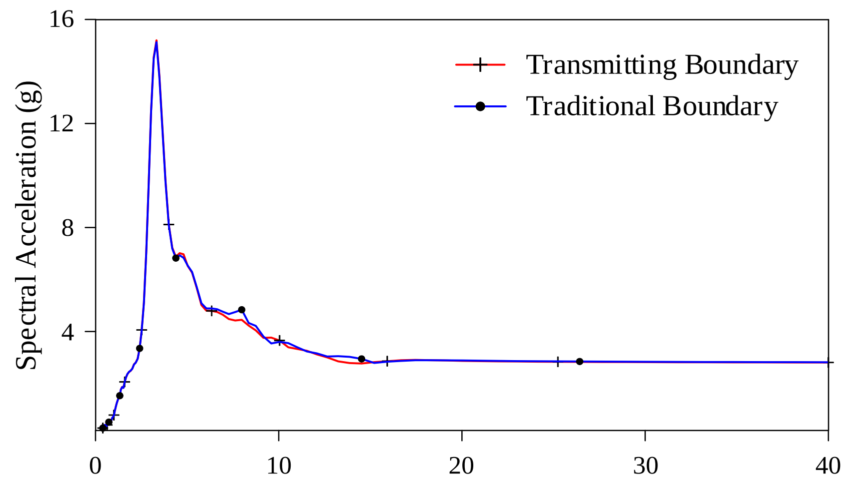
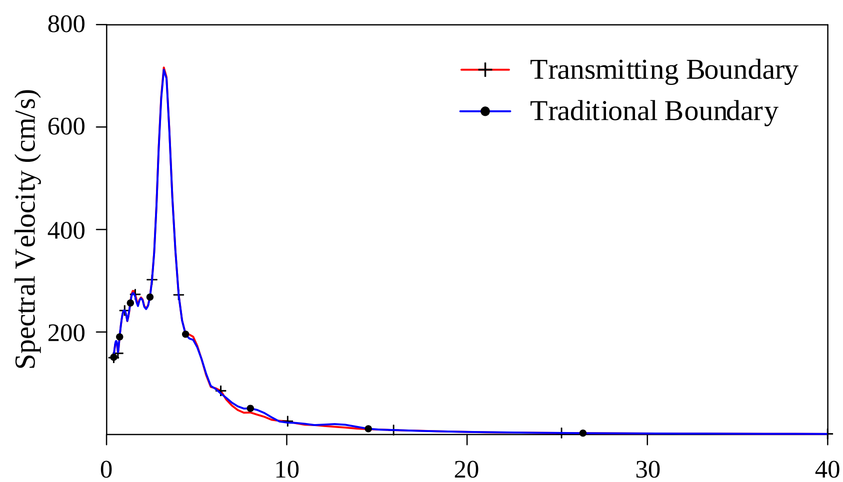

Spectral Acceleration (g)
0
4
8
12
16
0
10
20
30
40
1xH
2xH
3xH
4xH
5xH
Spectral Velocity (cm/s)
0
200
400
600
800
0
10
20
30
40
1xH
2xH
3xH
4xH
5xH
Spectral Displacement (cm)
0
10
20
30
40
50
0
10
20
30
40
1xH
2xH
3xH
4xH
5xH
Frequency (Hz)

Figure 6. Response spectrums at the dam crest for five different size of foundation model with traditional boundaries



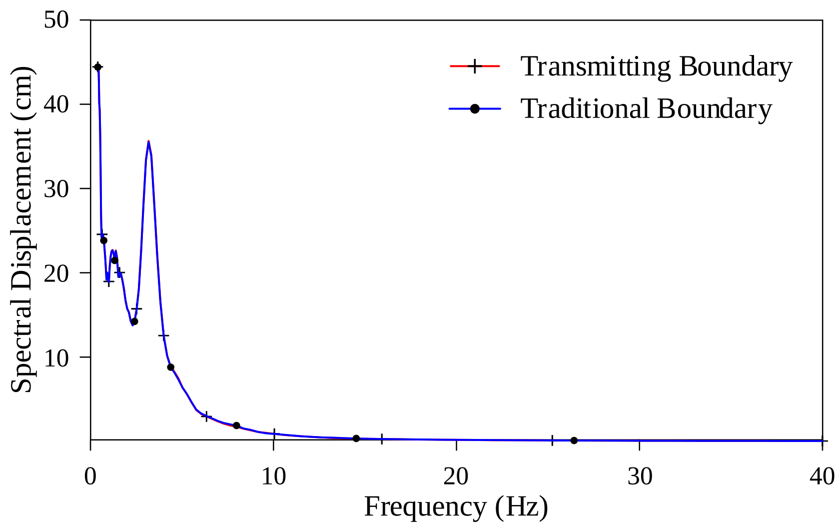



Figure 7. Response spectrums at the dam crest for traditional model with 5H foundation size and model with transmitting boundaries

## CONCLUSION

In this study, efficiency of transmitting boundaries is investigated for dynamic analysis of the soil-structure interaction systems and the results are compared with traditional soil-structure interaction model. In the light of the presented results, 5H distance from dam body in longitudinal direction is sufficient to model the soil-structure interaction of concrete gravity dams using traditional boundaries provided that the depth of the foundation model is assumed as 1H distance from dam base. In addition, the results obtained from a traditional soil-structure interaction model with 5H distance from dam body in longitudinal direction are approximately same with that from soil-structure interaction model using transmitting boundaries. The result represents that enormous soil volume can be eliminated and infinite soil media is easily represented with finite using transmitting boundaries since transmitting boundaries absorbs wave effects emanating from the structure.

## REFERENCES

[71] Lysmer, J. Udaka, T. Tsai, C.F. Seed, H.B. (1975) FLUSH, A Computer Program for Approximate 3-D Analysis of Soil-Structure Interaction Problems. EERC, 75(30), University of California, Berkeley, USA.

[72] Dumanoğlu, A.A. (1978) Dynamic Analysis of Partially Embedded Massive Structures. Ass. Prof. Dissertation, Turkey.

[73] Dumanoğlu, A.A. (1980) The Dynamic Soil-Structure Interaction Analysis of Embedded Structures with Non-Reflecting Boundaries. Bullettin of the Technical University of İstanbul, 33(1), İstanbul, Turkey.

[74] Lysmer, J. Kuhlemeyer, R.L. (1969) Finite Dynamic Model for Infinite Media. Journal of the Engineering Mechanics Division, ASCE.

[75] Richart, F.E. Woods, R.D. Hall, J.R. (1970) Vibration of Soils and Foundations. Frentice Hall, Inc.

[76] Graff, K.F. (1975) Wave Motion in Elastic Solids. Ohio State University Press.

[77] Clayton, R. and Engquist, B. (1977). Absorbing Boundary Conditions for Acoustic and Elastic Wave Equations. *Bulletin of the Seismological Society of America. 1529-1540.*

[78] Brebbia, C.A. Telles, J.C.F. Wrobel, L.C. (1984) Boundary Element Techniques. Springer-Verlag.

[79] Berenger, J. P. (1994) A Perfectly Matched Layer for the Absorption of Electromagnetic waves. *Journal of Computational Physics*. 185–200.

[80] Song, C. And Wolf, J.P (1996) Consistent Infinitesimal Finite-Element Cell Method: Three Dimensional Vector Wave Equation. International Journal for Numerical Methods in Engineering. 2189–2208.

[81] Wolf, JP. Song, C. (1996) Finite-Element Modeling of Unbounded Media, Wiley , New York.

[82] Tsynkov, S.V. (1998) Numerical Solution of Problems on Unbounded Domains: a review. Applied Numerical Mathematics, 465–532.

[83] Astley, R.J. (2000) Infinite Elements for Wave Problems: a review of current formulations and an assessment of accuracy. International Journal for Numerical Methods in Engineering, 951–976.