HYBRID WAVE FIELD METHOD FOR SEISMIC WAVE INPUT IN DYNAMIC SOIL-STRUCTURE INTERACTION PROBLEMS

X. Bao(1), JB. Liu(2), H. Tan(3), ST. Li(4), F. Wang(5), XF. Wang(6), DY. Wang(7)

(1) *Ph.D. Candidate, Tsinghua University, bx15@mails.tsinghua.edu.cn*
(2) *Professor, Tsinghua University, liujb@tsinghua.edu.cn*
(3) *Ph.D., China Academy of Railway Sciences Co.,LTD, huitanhui@163.com*
(4) *Ph.D. Candidate, Tsinghua University, list16@mails.tsinghua.edu.cn*
(5) *Ph.D. Candidate, Tsinghua University, wangf17@mails.tsinghua.edu.cn*
(6) *Ph.D. Candidate, Tsinghua University, wxf15@mails.tsinghua.edu.cn*
(7) *Ph.D., China Nuclear Power Engineering Co.,LTD, dongyangw@126.com…*

Abstract

The current seismic wave input methods are generally based on the already-known free wave field, which are further converted into the equivalent seismic loads on the cutoff boundaries. However, for most of the irregular topographies that may occur in practical engineering, such as slopes, regions and basins, the difficulties appear in determining the corresponding free wave fields through the near-field models, and thus the traditional seismic wave input methods are difficult to implement in such situations. In view of this, in this study we propose a hybrid wave field method suitable for the seismic wave input in irregular terrains. In this method, the equivalent input seismic loads on different cutoff boundaries are separately calculated, based on two free wave field and an incident wave field. For the two lateral sides of the near-field model, since their localized stratigraphic structures and the material properties are different with each other, the free-wave-field motions is obtained according to their corresponding flat ground models respectively. These free-wave-field motions are then transformed into the equivalent seismic loads through the lateral artificial boundary substructures. On the bottom of the near-field model, however, only the incident seismic wave field is considered, and it is converted into the equivalent seismic loads through the bottom artificial boundary substructure. Then, the process of seismic wave input in the soil-structure system with the irregular terrains can be accomplished by applying the corresponding equivalent input seismic loads on each boundary nodes. From the perspective of wave propagation, the incident waves are input through the three cutoff boundaries, interact with the local terrains and the structures and then generate the reflected and scattered waves. On the lateral sides, the reflected waves are offset by the equivalent seismic loads, and the scattered waves are absorbed by the artificial boundaries; while on the bottom side, since only the incident waves are considered during the calculation of equivalent seismic loads, both reflected and scattered waves propagate downward and finally absorbed by the artificial boundaries, which sets higher requirements for the wave absorption ability of the applied artificial boundaries. The hybrid wave field method is verified by comparing the numerical results obtained by the proposed method and the extended mesh solutions, which are obtained by increasing the length of the near-field domain so that the reflected waves will not return to the observation point within the calculation time. The results show that the proposed hybrid wave field method provides an effective approach to solve the seismic wave input problem in the soil-structure system where the free wave field cannot be predetermined, and the calculation accuracy can meets the engineering needs.

Keywords: seismic wave input; soil-structure interaction; irregular topography; boundary substructure method

1. Introduction

With the construction of large-scale buildings and the utilization of underground space, the dynamic soil-structure interaction (DSSI) has became one of the most focused research topics in earthquake engineering. For DSSI problems, the structures and the unbounded foundation together constitute a semi-infinite open system. Currently the numerical simulation is the most practical and commonly used method for the dynamic response analysis of such an open system.

Since the earthquake sources are usually far from the soil-structure interaction (SSI) region, a finite near-field calculation domain without the earthquake sources are usually intercepted to set up the numerical model. The artificial boundaries, which are also known as the absorbing boundaries or the nonreflecting boundaries, are applied on the truncation boundaries to absorb the outgoing scattered waves. The representative works on the artificial boundary techniques including the boundary element method[1], the scaled boundary finite element method[2], the perfected matched layer[3], the transmitting boundary[4] and the viscoelastic boundary[5]. However, after the application of the artificial boundaries, the seismic wave input problem, which aims to input the seismic waves into the near-field calculation domain without affecting the absorption of the scattered waves by the artificial boundaries, becomes a key issue to be settled.

Due to the limitations on the analysis method and the calculation techniques, in the early research on the seismic wave input, the complex refractions of seismic waves at the interlayer interfaces are usually ignored, and the seismic waves are assumed to be incident along the vertical direction. Based on this assumption, Joyner and Chen[6] deduced the equivalent seismic loads for one-dimensional viscous boundary to complete the seismic wave input in a one-dimensional soil layer model. Clough[7] used the stiffness of the foundation to convert the free-wave-field motions into the equivalent seismic loads and input them into the model of the soil-structure interaction system. However, because the inertial and damping forces of the soil layers are ignored, some certain errors may exist in the calculation results. Wolf[8] proposed the free-field boundary method for seismic wave input in the soil-structure interaction systems in 1989, which has a significant influence on the subsequent researches in this field.

The above seismic wave input methods, however, are mainly conducted and proposed for the case of vertically incident seismic waves. In fact, as the wave velocities of the soil layers generally increase with the increase of the burial depth, the propagation directions of the seismic waves always have a tendency of tilting upward. Therefore the vertical incidence of seismic waves is only reasonable for the wave propagation from the far-field sources. When a shallow-source earthquake occurs, the seismic waves are rarely incident vertically, but propagate upward at a certain angle. This phenomenon causes the non-uniform ground motions on the ground, which will have a significant impact on the seismic response of the structures. In order to consider the influence of the far-field infinite medium on the near-field model more reasonably and realize the oblique incidence of the seismic waves, Liu[9] proposed the wave method for seismic wave input, which converts the incident waves into equivalent seismic loads based on the viscoelastic artificial boundaries. The research team lead by Liu further developed this method by introducing the substructure model to calculate the equivalent seismic loads, and proposed the boundary substructure method (BSM)[10] and the internal substructure method (ISM)[11-12]. Bielak et al[13-14] proposed the domain reduction method (DRM), which considers the earthquake source and the propagation path of the seismic wave, and become one of the most commonly used seismic wave input methods for site seismic analysis.

However, for the irregular topographies such as ridges, basins or slopes, as shown in Fig. 1, the free wave field usually cannot be solved in advance. In order to accomplish the seismic wave input in those cases, an extreme large-scale background free field model need be established and the free field analysis should be conducted, which will cost tremendous computational resources. In this study, we proposed a hybrid wave field method on the basis of the boundary substructure method, to effectively accomplish the seismic wave input in the irregular topographies. Compared to the previous methods, the proposed method does not require the calculation of the entire free wave field in advance, therefore reduces the computational burden and improves the calculation efficiency.

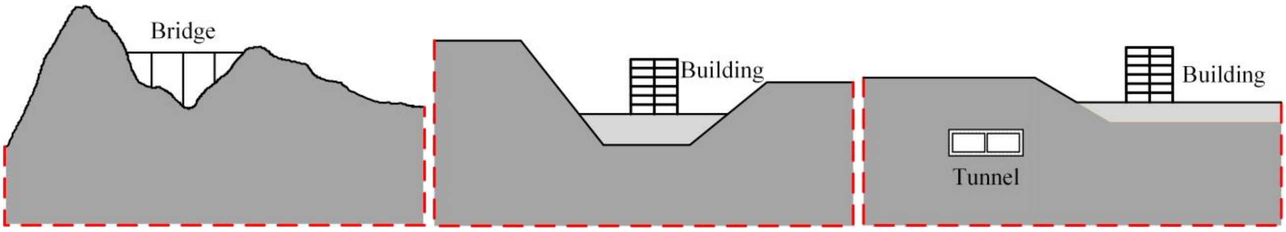


Fig. 1 –The typical irregular topographies

2. Hybrid wave field method for seismic wave input

Liu et al[10] proposed the BSM for seismic wave input in dynamic soil-structure interaction problems. According to the concept of BSM, as shown in Fig. 2, one should first conduct the free field analysis according to the seismic waves and the incident angles, then apply the free wave field motions on the nodes of the boundary substructure and conduct a dynamic analysis. The nodal reaction forces can be obtained, which are exactly the equivalent seismic loads. Those loads are then applied on the artificial boundary nodes of the SSI model, the process of seismic wave input can be accomplished through a dynamic analysis of the SSI system.

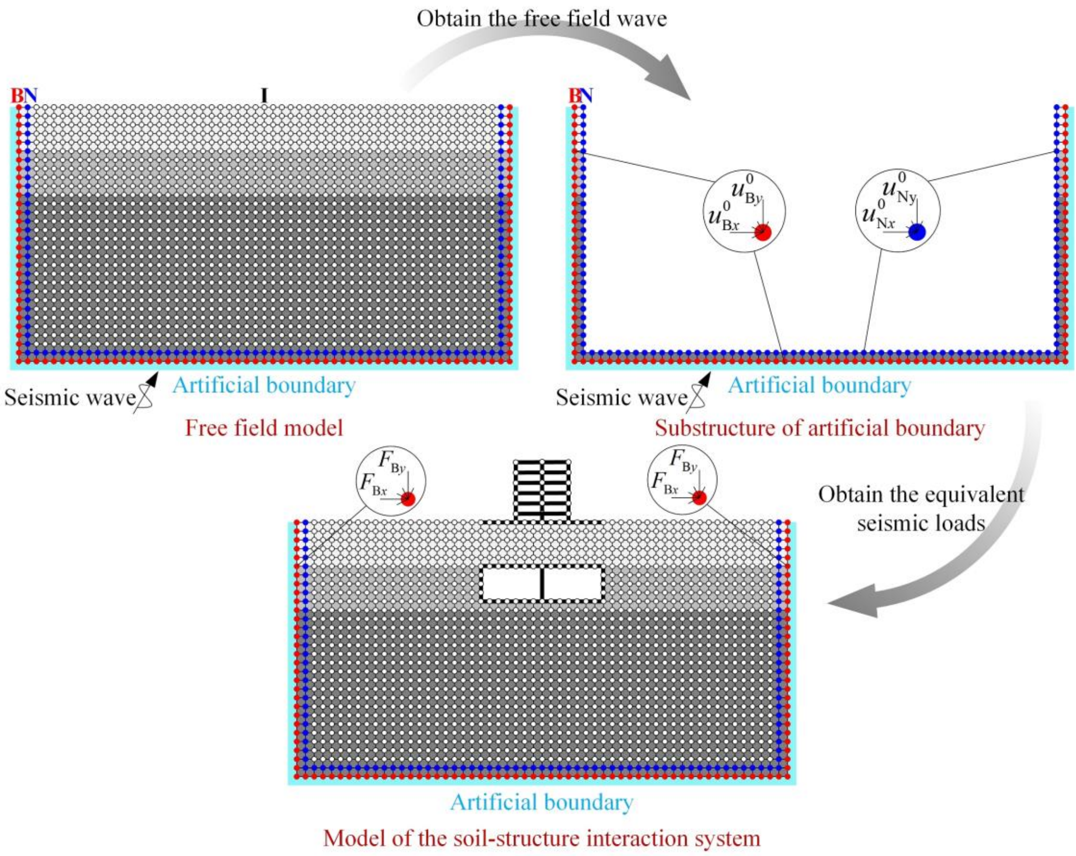


Fig. 2 –The principle and the calculation process of the boundary substructure method[10]

However, for the irregular topographies such as ridges, basins and slopes, as shown in Fig. 1, the topographic and stratigraphic conditions on the two sides of the near-field model are different. Therefore it is difficult to determine the free wave field in the entire calculation domain. To solve this problem, a hybrid wave field technology is proposed based on the concept of BSM, in which the input wave field is a hybrid form composed of the free wave field and the incident wave field. The calculation principle and implementation procedures of the proposed method are introduced in the cases of seismic wave vertical incidence and oblique incidence.

2.1 Vertical incidence of seismic wave

For the case of vertically incident seismic waves, we separate the artificial boundary substructure into three parts: the two lateral side substructures and the bottom substructure. For the two lateral sides of the near-field model, since their localized stratigraphic structures and the material properties are different with each other, the free-wave-field motions is obtained according to their corresponding flat ground models respectively. These free-wave-field motions are then transformed into the equivalent seismic loads through the lateral artificial boundary substructures. On the bottom of the near-field model, however, only the incident seismic wave field is considered, and it is converted into the equivalent seismic loads through the bottom artificial boundary substructure. Then, the process of seismic wave input in the soil-structure system with the irregular terrains can be accomplished by applying the corresponding equivalent input seismic loads on each boundary nodes. In this way, we proposed a hybrid wave field method for vertically incident seismic waves, the calculation principle is shown in Fig. 3. In this method, the waves are input into the calculation domain in a hybrid form composed of two free wave fields and an incident wave field.

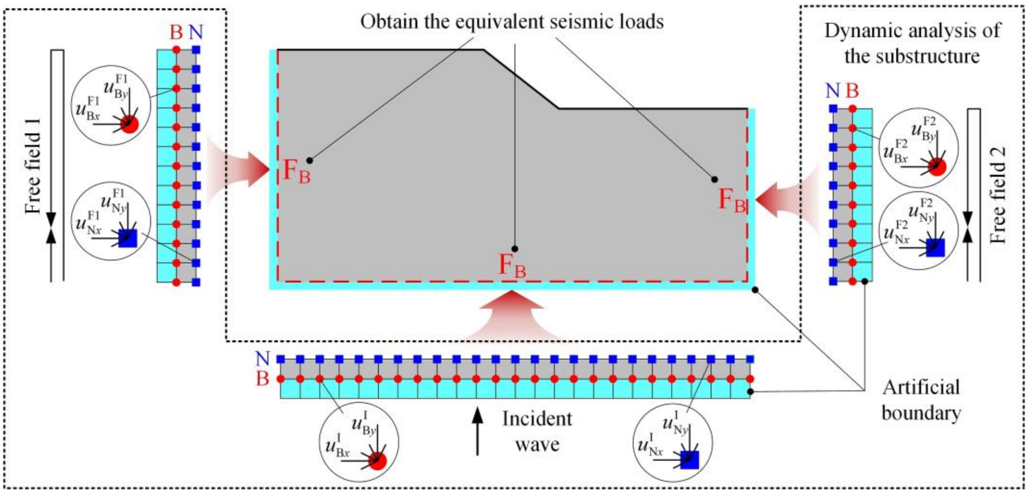


Fig. 3 – The principle and the calculation process of the hybrid wave field method: vertical incidence of seismic wave

From the perspective of wave propagation, the incident waves are input through the three cutoff boundaries, interact with the local terrains and the structures and then generate the reflected and scattered waves. On the lateral sides, the reflected waves are offset by the equivalent seismic loads, and the scattered waves are absorbed by the artificial boundaries; while on the bottom side, since only the incident waves are considered during the calculation of equivalent seismic loads, both reflected and scattered waves propagate downward and finally absorbed by the artificial boundaries.

The implementation procedure of the hybrid wave field method are proposed as following:

(1) Establish a localized near-field finite element model, and apply the artificial boundaries on the truncation boundary.

(2) Intercept the two lateral side boundary substructures and the bottom substructure from the entire model, which are composed of the artificial boundaries and a layer of elements adjacent to the artificial boundaries. Apply the corresponding free wave field motions and the incident wave motions on the nodes of

the lateral and bottom substructures, respectively, and conduct the dynamic analysis. The nodal reaction forces on the boundary nodes can be obtained, which are the equivalent seismic loads.

(3) Apply the equivalent seismic loads on the artificial boundary nodes of the near-field model. Then the seismic response of the irregular topography can be obtained through the dynamic calculation.

2.2 Oblique incidence of seismic wave

If the seismic waves are obliquely incident, the free wave field on the bottom boundary and the downstream boundary cannot be obtained before the calculation since the reflected and scattered waves in these area are unknown. In this situation, we use the free wave field the calculate the equivalent seismic loads on the upstream boundary and use the incident wave fields for the calculation of equivalent seismic loads on the bottom and downstream boundaries, as shown in Fig. 4. The reflected and scattered waves on the the bottom and downstream side are left to be absorbed by the artificial boundaries.

The implementation processes of the hybrid wave field method under the obliquely incident seismic waves are similar with the case of vertical incidence, except that the incident wave motions rather than the free-wave-field motions are applied on the downstream substructure in step 2.

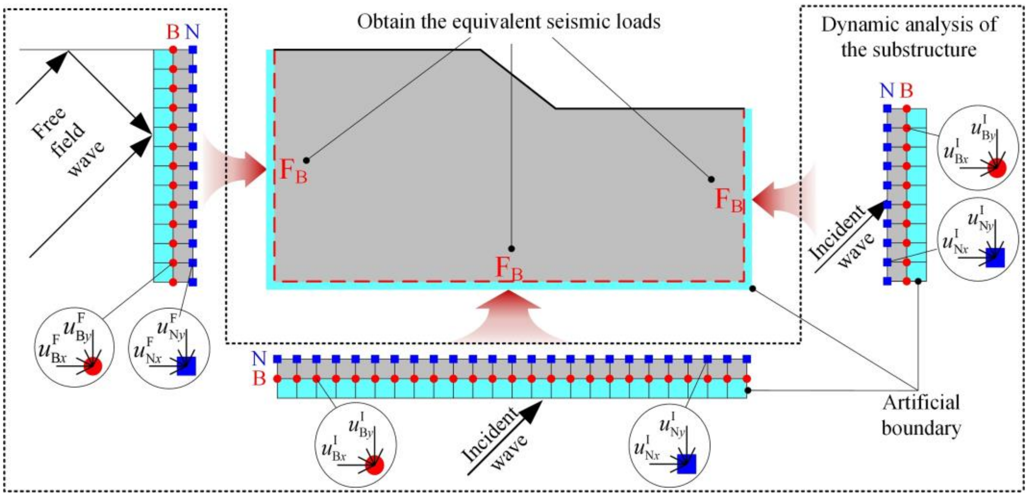


Fig. 4 – The principle and the calculation process of the hybrid wave field method: oblique incidence of seismic wave

3. Numerical examples

3.1 Vertical incidence of seismic wave

Then we will validate the proposed hybrid wave field method through several numerical examples. The first example is to simulate the vertical incidence of seismic wave in a slope site model. The computation model is shown in Fig. 5. The material properties are as follows: mass density ρ = 2000 kg/m^3, velocity of the shear wave c_s = 200 m/s and Poisson's ratio ν = 0.25. A, B and C are three observation points on the slope. A pulse wave shown in Fig. 6 is selected as the incident wave and is input vertically into the calculation model through the hybrid wave field method. The accuracy of the proposed method is verified by comparing the results with the extended mesh solutions, which is obtained by increasing the size of the calculation domain to ensure that the reflected and scattered waves cannot return to the observation points within the computational time.

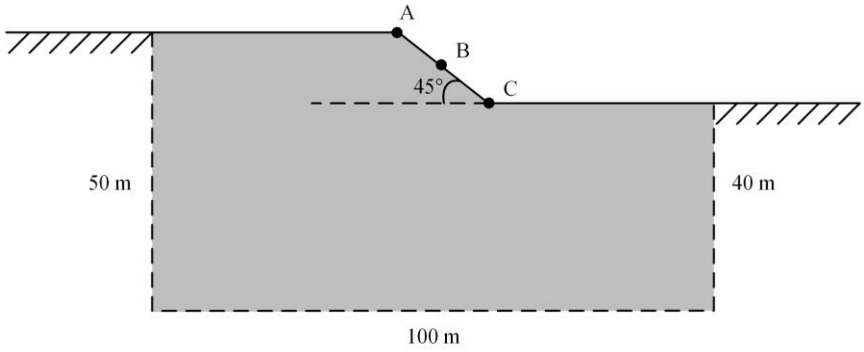
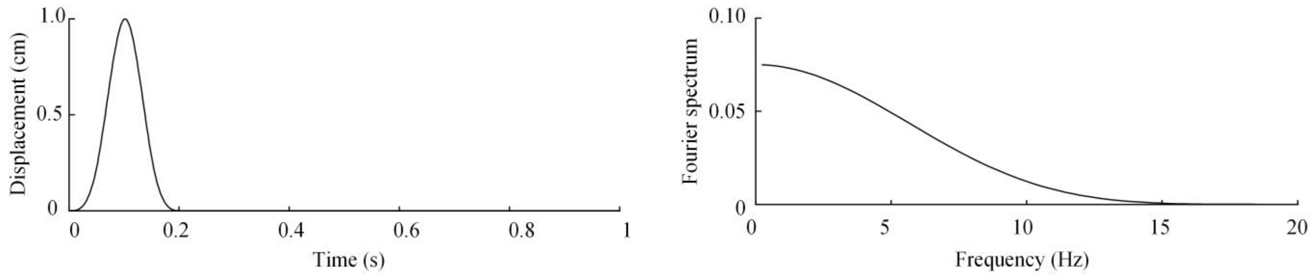


Fig. 5 – The near-field calculation model

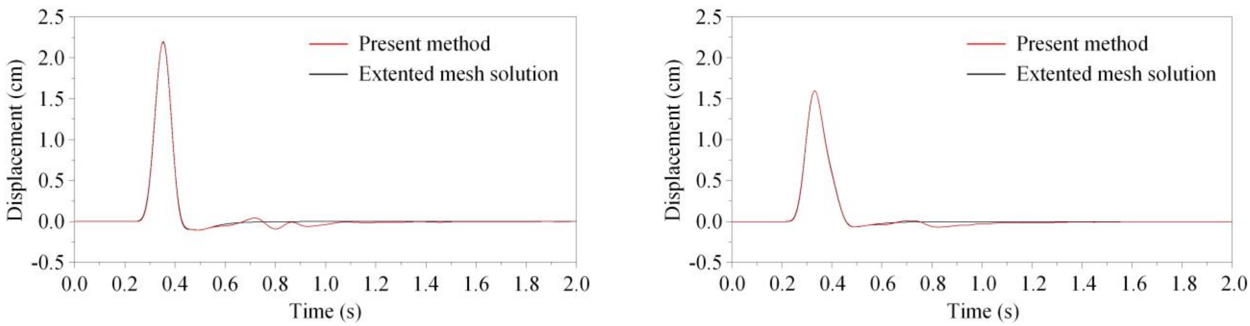


(a) Displacement

(b) Fourier spectrum

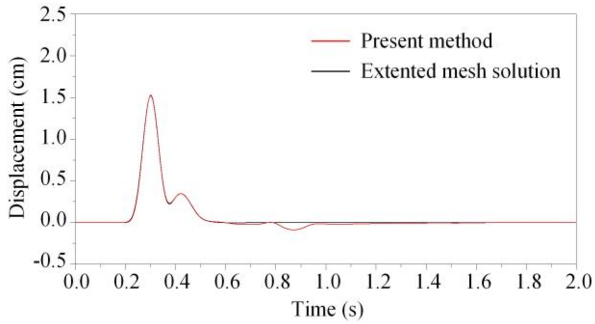
Fig. 6 – The displacement and Fourier spectrum of the incident pulse wave

The horizontal displacement on three observation points are plotted in Fig. 7. It can be seen that the peak seismic responses calculated through the hybrid wave field method agree well with the extended mesh solutions. But there are some small errors in the subsequent wave propagations caused by the incomplete absorption of the reflected waves by the bottom artificial boundary. Since the peak ground motion is generally the most important parameter for seismic design, the proposed method can be accepted for the seismic analysis of such a slope site model.



(a) A point

(b) B point

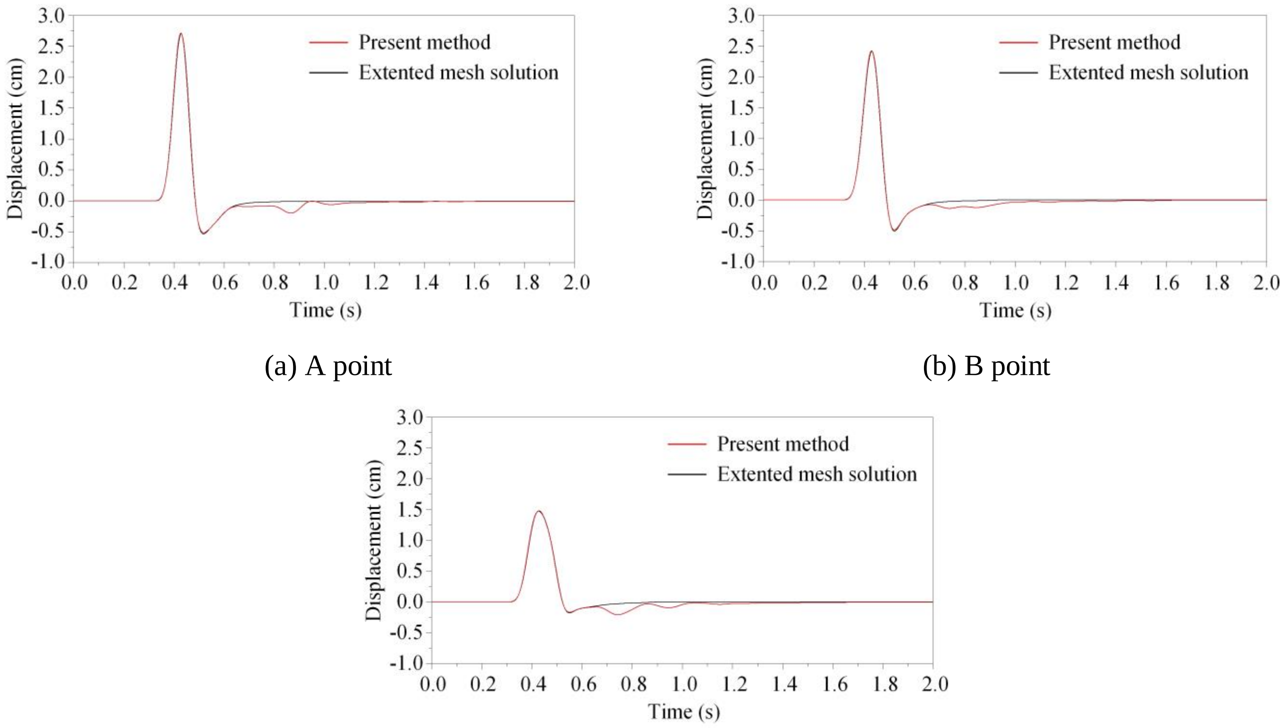


(c) C point

Fig. 7 – The horizontal displacement on the observation points under the vertical incidence of seismic wave

3.2 Oblique incidence of seismic wave

In this numerical example, the pulse wave shown in Fig. 6 is obliquely input into the slope site model through the proposed method, at an incident angle of 30°. The horizontal displacements on the observation points A, B and C are plotted in Fig. 8. Similar with the vertically incident case, the peak seismic response calculated by the proposed method provide nice accuracy, and small errors appear during 0.7 s-1.1 s.



(a) A point (b) B point

(c) C point

Fig. 8 – The horizontal displacement on the observation points under the oblique incidence of seismic wave

4. Conclusions

In this study, we propose a hybrid wave field method based on the concept of BSM to solve the wave input problems in the irregular topographies, in which the entire free wave field cannot be obtained in advance.

The input wave field of the proposed method is a hybrid form composed of the free wave field and the incident wave field. The calculation principle and implementation procedures of the proposed method in the case of vertically and obliquely incident seismic waves are introduced. Through the numerical examples, it has been validated that this method can accurately calculate the peak site seismic response. However, due to the incomplete absorption of the reflected waves by the artificial boundaries, some certain errors may occur after the wave front. Considering that the peak site seismic response are usually the key ground motion parameter for seismic design, and the proposed method can accurately measure the seismic amplification effect, this method is practical in the dynamic soil-structure interaction analysis considering the irregular topographies.

5. Acknowledgements

This work is supported by National Key Research and Development Program of China (2018YFC1504305) and National Natural Science Foundation of China (U1839201, 51878384). Their financial support is highly appreciated.

6. Copyrights

7. References

[1] Estorff OV, Antes H (1991): On FEM-BEM coupling for fluid-structure interaction analyses in the time domain. *International Journal for Numerical Methods in Engineering*, **31**(6), 1151-1168.

[2] Wolf J P, Song C (1995): Consistent infinitesimal finite-element cell method: in-plane motion. *Computer Methods in Applied Mechanics and Engineering*. **123**(3-4), 355-370.

[3] Hastings FD, Schneider JB, Broschat SL (1996): Application of the perfectly matched layer (PML) absorbing boundary condition to elastic wave propagation. *The Journal of the Acoustical Society of America*, **100**, 3061-3069.

[4] Liao ZP, Wong HL (1984): A transmitting boundary for the numerical simulation of elastic wave propagation. *International Journal of Soil Dynamics and Earthquake Engineering*, **3**(4), 174-183.

[5] Liu JB, Du YX, Du XL, Wang ZY, Wu J (2006): 3D viscous-spring artificial boundary in time domain. *Earthquake Engineering & Engineering Vibration*, **5**(1), 93-102.

[6] Joyner WB, Chen A (1975): Calculation of nonlinear ground response in earthquakes. *Bulletin of the Seismological Society of America*, **65**(5), 1315-1336.

[7] Clough RW (1985): Dynamic interaction effects in arch dams. University of California: Berkeley.

[8] Wolf JP (1989): Soil-structure-interaction analysis in time domain. *Nuclear Engineering & Design*, **111**(3), 381-393.

[9] Liu JB, Lu YD (1998): A direct method for analysis of dynamic soil-structure interaction based on interface idea. *Developments in Geotechnical Engineering*, **83**(3), 261-276.

[10] Liu JB, Tan H, Bao X, Wang DY, Li ST (2019): Seismic wave input method for three-dimensional soil-structure dynamic interaction analysis based on the substructure of artificial boundaries. *Earthquake Engineering & Engineering Vibration*, **18**(4), 747-758.

[11] Liu JB, Bao X, Wang DY, Tan H, Li ST (2019): The internal substructure method for seismic wave input in 3D dynamic soil- structure interaction analysis. *Soil Dynamics & Earthquake Engineering*, **127**, 105847.

[12] Bao X, Liu JB, Wang DY, Li ST, Wang F, Wang XF (2019): Modification research of the internal substructure method for seismic wave input in deep underground structure-soil systems. *Shock & Vibration*, **2019**, 5926410.

[13] Bielak J, Loukakis K, Hisada Y, Yoshimura C (2003): Domain reduction method for three-dimensional earthquake modeling in localized regions, Part I: Theory. *Bulletin of the Seismological Society of America*, **93**(2), 817-824.

[14] Yoshimura, C, Bielak J, Hisada Y, Fernandez A (2003): Domain reduction method for three-dimensional earthquake modeling in localized regions, Part II: Verification and Applications. *Bulletin of the Seismological Society of America*, **93**(2), 825-841.