Influence of the Lateral Heterogeneity of Shallow Sediments on Site Effects in the Yuxi Basin

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Abstract—As computing power and ground motion studies using numerical simulation methods have continuously improved, velocity model accuracies have become bottlenecks for simulation result accuracies. The characteristics of a hydrodynamic sedimentary environment in the Yuxi Basin are used as a classification standard, and a refined velocity model that depends on the lateral heterogeneity in sediments is constructed. The results of the lateral heterogeneity model are compared with those of the lateral uniformity model, and the distributions of the displacement peak ratio, focusing effect and edge effect change due to the refined basin structure. For the 4% of the surface area that is in the region with the largest amplification factor, the difference between the two models is greater than 20%, and this difference for nearly half of the surface area is greater than 5%.

Keywords: Sedimentary environment, velocity model, lateral heterogeneity, simulation accuracy.

1. Introduction

Sedimentary basins have significant amplification effects on ground motion. Studies have shown that this basin effect is an important factor that causes seismic hazards and local ground motion anomalies. In addition, many sedimentary basins have complex velocity structures, which are typical complex site conditions. In many cases, these complex structures aggravate seismic hazards, such as in the Mexico earthquake (Eduardo, 1999), Northridge earthquake (Graves, 1998), and Kobe earthquake (Kawase, 1996).

A numerical simulation is a common method with which to study the site effect caused by the velocity structures of complex basins. This method can simulate seismic wave propagation in a medium with arbitrary complex structures and calculate the ground motion. In recent years, as computer technology has developed, the accuracy of numerical simulations has improved. Daniel Roten et al. (2016) simulated an MS 7.7 earthquake in the southern San Andreas fault with the National Center for Supercomputing Application (NCSA) Blue Waters and Oak Ridge Leadership Computing Facility (OLCF) Titan, with a cut-off frequency of 4 Hz and a spatial resolution of 25 m. The large-scale nonlinear seismic simulation of the Tangshan earthquake carried out by Haohuan Fu, Conghui He and Xiaofei Chen (2017) that considered Taihu Lake in Shenwei had a cut-off frequency of 18 Hz and a spatial resolution of 8 m.

However, numerical simulation theory is based on an accurate underground velocity structure model, and the accuracy of the model directly affects the accuracy of the simulation results. Establishing an accurate underground velocity structure model requires a large amount of geophysical exploration data, which is expensive and difficult to carry out in cities with dense populations and buildings.

1.1. Basin Structure Model Construction

A basin structure model is usually built from various geophysical data and is upgraded continuously. Jachens et al. (1997) established a 3D model of the basement interface in the Santa Clara Valley area with the gravity inversion method, and the model in the region was continuously improved with updated data (Jachens et al., 2001, 2005). Hole et al. (2000) used seismic tomography to further improve the velocity structure of the model. Based on the work of Jachens et al., (2001, 2005), Hartzell et al. (2006) established a more accurate 3D geological and velocity structure model in the Santa Clara valley...
area. Not only were borehole and seismic reflection data added, but microtremor data were also used to modify the surface shallow shear wave velocity. Lee, et al. (2014) applied the full-3-D tomography (F3DT) method based on a combination of the scattering-integral method (SI-F3DT) and adjoint-wavefield method (AW-F3DT) and released the Southern California Earthquake Center (SCEC) velocity model version 4.0 (CVM-S4).

Koketsu and Higashi (1992) obtained the shape of the basement and the stratification of sedimentary strata in the Tokyo area of the Kanto Basin by seismic reflection based on 63 active blasts over 14 years. Yamanaka and Yamada (1999, 2003) used microtremor data; Afnimar et al. (2003) used the gravity inversion method to build a 3D model of the region; and Miyake et al. (2006) integrated previous models to obtain a more accurate 3D model. Kazuki Koketsu et al. (2009) proposed a standard method for constructing 3D velocity structures of urban basins in Japan that includes the joint inversion of seismic and gravity exploration, and they applied the program to the Tokyo metropolitan area (TMA) in the Kanto Basin.

In addition, the following authors constructed 3D velocity models of sedimentary structures: Magistrale et al., (1996, 2000) and Süss and Shaw (2003) in the Los Angeles region, Kagawa et al. (2004) in Osaka, Pitarka et al. (2004) in the Gulf of Putjit, Manakou (2010) in the Miguton region of northern Greece and Irene Molinari et al. (2015) in the Po Plain, Italy.

1.2. Influence of the Refined Model

As research has improved, numerical simulations have developed more requirements for basin models. The models established by seismologists in a given region have been modified many times to improve the accuracy of the calculation. In addition, the accuracy of the models and comparisons between different models have been studied.

Stephen Hartzell et al. (2010) added a random velocity disturbance to the model of the San Francisco Bay area with the 3D Von Karman random medium and found obvious deviations. Ricardo Taborda and Jacobo Bielak (2013) used different seismic velocity models in southern California (CVM-s and CVM-H) to simulate the 2008 Mw 5.4 Chino earthquake. They believed that strong ground motion was very sensitive to the difference between the basin and shallow structure in the model, and the uncertainty in the shallow layer in the model had a great influence on the results, especially at high frequencies. Imperatori and Gallovic (2017) studied the model of the San Francisco Bay area based on the 2014 Nannapa M6.0 earthquake and considered that a smoother velocity model (reducing the strong velocity contrast between basin fillings and bedrock) could effectively reduce false seismic wave oscillations.

Shunsuke Takemura et al. (2015) believed that the lateral heterogeneity of seismic velocity in sediments determined the propagation characteristics of surface waves in the northern Kanto Basin in Japan in a simulation study. Dhakal et al. (2013) compared three 3D velocity models (J-SHIS (2009), HERP (2012) and Yamada and Yamanaka (2012)) in the Kanto region of Japan by using the finite difference seismic simulation method. Each model yields great differences at the edge of the basin and may need further modification.

In summary, many scholars believe that the accuracy of 3D velocity structure models needs to be further improved in shallow layers and the edges of basins, and the lateral heterogeneity of the sedimentary medium might have a greater impact on the simulation results. The possible reason for this greater impact is that the shear wave velocity of near-surface sites is very low. When the seismic wave propagates through a shallow layer in a model, it produces obvious energy accumulation, which greatly enhances the surface wave and amplification effects. Therefore, using a numerical simulation method to predict ground motion requires a high accuracy for the shallow layer of the 3D velocity model.

Based on the distribution characteristics of the bedrock surface depth in the Yuxi Basin, combined with drilling and seismic reflection data, a 3D velocity structure model of the Yuxi Basin was established in this paper. In combination with the influence of the sedimentary environment on the physical properties of the shallow sediments in the Yuxi Basin, a refined model with laterally heterogeneous Quaternary sediments was further established. Numerical simulations of the two models were
carried out, and the influence of the improvement in the lateral model accuracy on the site effect was analysed. This study provides a reference for understanding the influence of insufficient model accuracy on calculations.

2. Stratification Structure of the Sediments in the Yuxi Basin

The Yuxi Basin is located in Yunnan Province, China, as shown in Fig. 1. It is one of the larger sedimentary basins in the southern segment of the Puduhe fault zone, and the thickness of sedimentary cover in the basin varies greatly. Based on 17 seismic reflection profiles and 16 borehole data points, and combined with the bedrock surface model of the Yuxi Basin given by He et al. (2013), a vertical layered structural model of sedimentary soils in the Yuxi Basin was constructed. Figure 2 shows the distribution map of bedrock surface depth in the Yuxi Basin (He Zhengqin et al., 2013).

The area composed of purple and yellow in the lower left of the figure is the location of the Yuxi basin; it is located in Yunnan Province, China.

In the figure, the black solid lines are the 17 reflection lines (He Zhengqin et al., 2013), and the red dots are the 16 boreholes. The maximum thickness of sedimentary soil layer is approximately 800 m in the central and northern areas of the basin. The bedrock surface is based mainly on reflection data, and the lateral heterogeneity in the shallow sediments is based mainly on borehole data.

He Zhengqin et al. (2013) carried out a phase contrast analysis of effective reflection and cophase axis tracing according to the reflection lines. First, the continuous tracing of the standard horizon (such as bedrock reflection) was controlled. Second, the horizon in the overburden was compared and analysed. In combination with the stratigraphic structure of a geothermal borehole along the L6–2 survey line in the southern Yuxi Basin, horizon calibration and sequence classification of the temporal seismic reflection sections were carried out. At L2, along the survey line in the north-central basin, six reflected
wave groups are visible in the temporal section of the thick sedimentary layer, as shown in Fig. 3. Among them, five reflected wave groups (blue lines in the figure) are stratigraphic interfaces with large velocity differences in the basin, and the last reflected wave group with the strongest energy (the red line in the figure) is the reflected wave from the top of the bedrock. At L1 in the northern part of the basin and L6 in the southern part of the basin, only four of the six reflected wave groups can be identified, and among these, three are associated with shallow interfaces, and one is associated with the top of the bedrock.

Therefore, in the thickest sedimentary soil area of the Yuxi Basin, the sediments can be divided into six layers according to the results of seismic reflection exploration. As the bedrock near the edge of the basin shallows, the velocity stratification at deeper depths gradually disappears, and the velocity stratification at shallower depths continues to extend to the edge of the basin.

The L2 survey line is in the northern middle area of the Yuxi Basin, crossing over the thickest area of sedimentary soil. The blue lines in the figure show the reflected waves associated with the sedimentary soil interfaces, and the red lines show the reflected waves associated with the top of the bedrock. Due to the Puduhe Fault, there are six reflected wave groups in the thickest area, five groups in the shallower area and one group in the edge area.

Figure 4a shows the depth of the first layer of the model, which is based on both the reflection line and borehole data. According to borehole histograms, this layer is Quaternary sedimentary soil, while the other layers are Tertiary sediments. Figure 4b shows the depth of the second layer.

Figure 5 shows the depth of the third layer (a) and the fourth layer (b) of the model. As the basin deepens, the extent of the sedimentary soil becomes smaller.

Figure 6 shows the depth of the fifth layer (a) and sixth layer (b) of the model. This two layers only exist in the deepest part of the basin.

According to the bedrock depth distribution and the results of seismic reflection exploration in the Yuxi Basin, the kriging method was used to differentiate reflection line interfaces, and the distribution characteristics of the interfaces of five sedimentary layers with different velocities in the basin were obtained, as shown in Figs. 4–6. Based on these five sedimentary layers and the bedrock depth distribution, a velocity structure model was constructed with only vertical stratification (hereinafter referred to as model 1).

3. Laterally Heterogeneous Velocity Structure Model of the Yuxi Basin

To analyse the influence of the model accuracy on the simulation results, this paper combines the
influence of the sedimentary environment on the physical properties of sediments in the Yuxi Basin and further establishes a more refined basin model that considers sedimentary environmental factors.

3.1. Lateral Heterogeneity of Quaternary sediments

Based on data from 16 boreholes (Table 1), the sedimentary characteristics of Quaternary soil layers in the Yuxi Basin were classified according to the psephicity and particle size of sediments, and the wave velocity characteristics were analysed. The classification method is as follows: the gravel layers are classified as having low psephicity. The gravelly sand layers dominated by round gravel are classified as having moderate psephicity. The fine sand layers are classified as having high psephicity. The particle size is divided into large (2–20 mm and above), middle (2–10 mm) and small (less than 2 mm) categories.

The linear fitting results of the velocity–depth relationship that are classified according to the particle size classification are shown in Fig. 7 (a). In the figure, the blue line is the velocity–depth relationship of soil with large particle sizes, the red line is that with medium particle sizes and the black line is that with small particle sizes; therefore, the shear wave velocity is significantly related to the sediment particle size. The larger the sediment particles are, the higher the shear wave velocity is. The results according to the psephicity are shown in Fig. 7b. In the figure, the black line is the velocity–depth relationship of low-psephicity soil, the red line is that of medium-psephicity soil and the blue is that of high-psephicity soil; therefore, the shear wave velocity has a certain relationship with the psephicity
of particles, and the higher the psephicity is, the lower the wave velocity is.

The lines are the fitting results, and the points are the data points used for fitting, corresponding to the colours of the lines. In Fig. 7a, the lines of different particle sizes are significantly separated; the larger the sediment particles are, the higher the shear wave velocity is. In Fig. 7b, the lines of different psephicity values are significantly separated; the higher the psephicity is, the lower the wave velocity is.

It is likely that the shear wave velocity of shallow sediments in the Yuxi Basin is related to the hydrodynamic environment. Specifically, the longer the sediment particles are transported in the water, the higher the psephicity is, and the lower the wave velocity of the associated sedimentary layer is. In addition, the sediment particle size is related to the transport capacity of water flow. Small particles are often deposited downstream of the water system, and the wave velocity of the formed sedimentary layer is low. In this paper, the velocity model is further divided according to the characteristics of the velocity changes in the sediments.

To establish the laterally heterogeneous velocity structure model that considers the influence of the sediment psephicity and particle size, this paper divides the shallow Quaternary strata formed in the Yuxi Basin into three categories.

The first type is the strata formed by proluvial deposits and slope wash, whose sediment particles have a short transport distance in water, are large and have poor sorting and low psephicity. In this paper, the gravel layers, as well as the gravelly sand layers
with larger particles, are classified as this type. Thus, the thickness distribution diagram of this classification stratum is obtained, as shown in Fig. 8a. This map shows the distribution of the main proluvial deposits and slope wash during the formation of Quaternary strata in the Yuxi Basin. The Quaternary sedimentary strata in the Yuxi Basin are divided into two parts based on the area with dense contour lines, as shown in Fig. 8b. The red part in the figure is dominated by proluvial and slope sedimentary environments.

Figure 8a shows the total thickness of the gravel and gravelly sand layers, which are considered to be formed in proluvial and slope wash environments. As a result of Fig. 8a, Fig. 8b shows the area dominated by proluvial and slope sedimentary environments.

Figure 8c shows the total thickness of the fine sand, gravel–sand with smaller particles and pebble layers, which are considered to be formed in fluvial environments. As a result of Fig. 8c, Fig. 8d shows the area dominated by fluvial sedimentary environments.

The second type is the strata formed by fluvial deposits, and the sediment particles have a long transport distance in water, are small, and have good sorting and high psephicity. In this paper, fine sand layers, as well as smaller particles in the gravel–sand layer and gravel layers with more pebbles, are classified as this type. Thus, the thickness distribution diagram of the shallow strata formed by alluvial deposits in the Yuxi Basin is obtained, as shown in Fig. 8c. This figure shows the distribution of alluvial layers during the formation of Quaternary strata in the Yuxi Basin. The blue solid line in the figure is the Yuxi River and its tributaries in the basin. The strata dominated by alluvial river deposits are consistent
with the river distribution in the Yuxi Basin. The Quaternary sedimentary layer in the Yuxi Basin is divided into three parts based on the area with dense contour lines, as shown in Fig. 8d. The orange part in the figure is the area dominated by an alluvial sedimentary environment.

As shown in the figure, the distribution of proluvial and slope environments (9a) and the distribution of fluvial environments (9b) are homologous with the distribution of shear wave velocity (9c). Based on comprehensive consideration of the distribution characteristics of sedimentary environment and shear wave velocity, the Quaternary strata in the Yuxi Basin can be divided into three areas (9d): proluvial and slope area, fluvial area and secondary clay area.

The third type is the secondary clay layer that formed by secondary sediments from the impacts of rivers and floods and small muddy clay layers; this type is mainly distributed in the southern part of the basin and has a relatively low shear wave velocity.

Based on shear wave logging data from boreholes, the equivalent shear wave velocity distribution trend of Quaternary shallow strata in the Yuxi Basin is obtained. A comparison of the mean shear wave velocity (Fig. 9c) of the shallow Quaternary strata in the Yuxi Basin with the proluvial, slope wash (Fig. 9a) and river impact areas (Fig. 9b) shows that the boundary lines of the proluvial, slope wash and river impact areas are all located in areas with large velocity gradients and are basically consistent with the trend of the isoline.

Therefore, when modelling the velocity structure of the Yuxi Basin, the influence of the sedimentary environment can be considered, and the Quaternary strata in the Yuxi Basin can be divided into three parts according to the lateral change in the wave

| No | Id  | Longitude | Latitude | Depth (m) | Altitude (m) | VS20 (m/s) |
|----|-----|-----------|----------|-----------|--------------|------------|
| 1  | BH1 | 102.55    | 24.45    | 80.2      | 1686         | 277        |
| 2  | BH2 | 102.55    | 24.44    | 84.87     | 1666         | 222        |
| 3  | BH4 | 102.53    | 24.42    | 131.8     | 1650         | 268        |
| 4  | BH5 | 102.57    | 24.42    | 82.6      | 1660         | 227        |
| 5  | BH6 | 102.55    | 24.41    | 81.8      | 1644         | 234        |
| 6  | BH7 | 102.51    | 24.40    | 83.0      | 1633         | 233        |
| 7  | BH8 | 102.54    | 24.38    | 82.7      | 1630         | 172        |
| 8  | BH9 | 102.52    | 24.38    | 82.5      | 1627         | 239        |
| 9  | BH11| 102.50    | 24.36    | 82.0      | 1644         | 212        |
| 10 | BH13| 102.52    | 24.35    | 83.0      | 1622         | 218        |
| 11 | BH14| 102.49    | 24.35    | 80.4      | 1619         | 224        |
| 12 | BH15| 102.51    | 24.33    | 82.3      | 1626         | 203        |
| 13 | BH16| 102.50    | 24.32    | 104.0     | 1634         | 157        |
| 14 | BH18| 102.53    | 24.33    | 100.2     | 1635         | 210        |
| 15 | BH19| 102.57    | 24.38    | 121.4     | 1635         | 242        |
| 16 | BH20| 102.57    | 24.38    | 139.4     | 1638         | 239        |
velocity, as shown in Fig. 9d. The red area in the figure is dominated by proluvial deposits and slope wash, with large particles, poor sorting and low psephicity, and the shear wave velocity is high. The orange area is dominated by a river alluvial layer, with small particles, good sorting, high psephicity, and moderate shear wave velocity. The yellow area is the secondary clay layer and small muddy clay layer formed by secondary sediments from the impacts of rivers and floods, and the shear wave velocity is low.

### 3.2. Lateral Heterogeneity of Tertiary Sediments

Figure 10 is based on the P-wave velocity in the reflection lines. After the linear fitting of the P-wave velocity and the depth, the average velocity at the
depth 350 m is selected to show the velocity distribution of deep sediments in the Yuxi Basin. Based on comprehensive consideration of the Puduhe fault and the P-wave velocity distribution, the Tertiary strata in the Yuxi Basin can be divided into eastern and western two parts.

According to the characteristics of 17 shallow reflection lines and the Puduhe fault, this paper analyses the P-wave velocity distribution characteristics of the deep sediments in the Yuxi Basin, as shown in Fig. 10. In the diagram, the red dashed line is the Puduhe fault; the thicker line is the main part of the fault. The blue solid lines are the locations of the reflection lines. The figure shows that the wave velocity distribution in the deep sediments in the Yuxi Basin is related to the Puduhe fault. The velocity on the western side of the main fault is lower than that on the eastern side.

In summary, the first Quaternary layer in the above vertical stratification model can be subdivided into three parts, which represent the three regions of strata formed in different sedimentary environments; these regions are referred to as “North”, “Mid” and “West” in Table 2. The remaining five Tertiary layers are subdivided into two parts, which represent two regions on both sides of the main part of the Puduhe fault; these regions are referred to as “East” and “West” in Table 2.

4. Analysis of the numerical simulation and results

The authors perform numerical simulation research on the basin effect in the Yuxi Basin (Tiefei Li 2021). In that study only the vertical stratification model given in Sect. 2 of this paper (hereafter referred to as model 1) was used. The Qujiang fault near the Yuxi Basin is selected as the seismogenic fault (the seismogenic fault of the 1970 Tonghai earthquake). The propagation of strong ground motion and the source of faults are simulated by using the finite difference method of velocity and stress recursion (Jinping Guo, 2016). The ground motion wave field at the bottom of the bedrock in the Yuxi Basin is used as the ground motion input.

In this paper, the same seismic input is used to simulate the refined mode (hereafter referred to as model 2) and analyse the influence of the lateral heterogeneity of sediments on the basin effect. The model parameters are given in Table 2. Model 1 and model 2 have the same node grid and different element parameters.

The maximum displacements of the input are 0.02857 m in the E-W direction and 0.03803 m in the N–S direction. The numerical simulation uses the displacement input. The distribution of the displacement magnification in the E–W, N–S and vertical directions is calculated. The maximum frequency of the simulation is 1 Hz, the minimum wave velocity of the model is 300 m/s, and the grid spacing is 30 m.

Figure 11 shows the magnification distribution in model 2. It is calculated based on the peak ground displacement and the peak input displacement. The result of model 1 was previously published (Tiefei Li 2021, https://doi.org/10.1007/s10950-020-09979-4).

Figure 11 shows the distribution of the peak ground displacement magnification of E-W and N–S
ground motions in the Yuxi Basin by considering the influence of sedimentary environment (model 2). The figure shows that there are obvious focusing effects and edge effects in the results. Among these effects, the distribution of the large amplification factor of the E-W ground motion caused by the basin focusing effect is complex. This distribution is mainly concentrated in the area around the deepest sediments in the northern part of the basin, the area surrounding the deepest sediments in the middle of the basin, and the area with low wave velocities and soft soil in the southern part of the basin. This distribution is related to the distribution of medium-depth stratigraphic interfaces, such as the second and third layers in the model. Its extreme value is more than 2 times the normal values and is not located in the deepest area of the basin but rather on the south edge, which may be the result of the combined action of the edge effect and the low wave velocity. The basin focusing effect of N-S seismic amplification is located in the sediments in the deepest part of the basin. The edge effect of the E–W earthquake is located on the northern edge of the basin, while the edge effect of the N–S earthquake is located on the eastern and western sides of the basin, and the western edge effect is more significant than the eastern edge effect. Compared with the simulation results of model 1, the magnification distribution, basin focusing effect and edge effect of model 2 are similar to those of model 1, but the distribution positions are different.

Figure 12 shows a comparison of time domain records for the two models; the red line is mode 2, and the black line is model 1. Figure 12a shows node 456,464, which has the strongest focusing effects in the northern part of the basin; Fig. 12b shows node 468,400, which shows the strongest focusing effects in the south.

As shown in Fig. 12, in the comparison of a single node, the shape of the time domain records are similar, and the difference is mainly reflected in the amplitude.

Figure 13 shows the distribution ratio of the peak displacements of model 2 and model 1, indicating the difference between the calculation results of the two models. As shown in the diagram, the difference between the two models has no obvious relationship with the uneven lateral boundary of the shallow sedimentary layer because the displacement cannot show the frequency domain characteristics of the seismic time domain record. Due to the influence of the Puduhe fault on deep sediments, the differences in the results tend to be located along the fault. At the same time, the two models show obvious regional differences in terms of the edge effects; therefore, the lateral heterogeneity of the sedimentary layer is coupled with a complex basin structure, which has a complex impact on simulations of the site and basin.

### Table 2

| Depth (m) | Young’s Modulus (MPa) | Density (g/cm³) | Poisson’s ratio | Shear wave velocity (m/s) | Damping ratio |
|----------|-----------------------|----------------|----------------|---------------------------|--------------|
| Layer 1 North | 1069.2                | 2000           | 0.32           | 450                      | 0.062        |
| Layer 1 Mid  | 762.4                 | 2000           | 0.32           | 380                      | 0.062        |
| Layer 1 South | 475.2                 | 2000           | 0.32           | 300                      | 0.062        |
| Layer 2 West | 1725.4                | 2100           | 0.31           | 560                      | 0.06         |
| Layer 2 East | 2253.6                | 2100           | 0.31           | 640                      | 0.06         |
| Layer 3 West | 3228.7                | 2150           | 0.30           | 760                      | 0.058        |
| Layer 3 East | 3944.3                | 2150           | 0.30           | 840                      | 0.058        |
| Layer 4 West | 7448.3                | 2200           | 0.28           | 1150                     | 0.056        |
| Layer 4 East | 8800.0                | 2200           | 0.28           | 1250                     | 0.056        |
| Layer 5 West | 10,333.5              | 2250           | 0.26           | 1350                     | 0.054        |
| Layer 5 East | 11,921.1              | 2250           | 0.26           | 1450                     | 0.054        |
| Layer 6 West | 12,937.5              | 2300           | 0.25           | 1500                     | 0.052        |
| Layer 7 East | 14,720.0              | 2300           | 0.25           | 1600                     | 0.052        |
| Bedrock    | 56,160.0              | 2600           | 0.2            | 3000                     | 0.05         |
Figure 11
Distribution of the displacement magnification of the east–west (a) and north–south (b) seismicity in model 2

Figure 12
E-W time domain records for the two models in the area, with focusing effects in the north (a) and south (b)
effects. The locations of the focusing and edge effects have changed, and the trend cannot be assessed according to the difference in the parameters at a single calculation point. In other words, after adding the lateral heterogeneity of the sediments affected by the sedimentary environment, due to the basin effect, the magnification of seismic waves is affected by the overall velocity structure of the basin, and the relationship with the specific layered interface is not obvious. Moreover, the model refinement has a greater impact on the basin edge effect.

In Fig. 13, the red, orange and pink areas indicate that the model 2 magnification is larger, the blue and green areas indicate that the model 1 magnification is larger, the white area indicates that the magnification is similar. The value is the displacement magnification ratio.

Figure 14 shows the proportional distribution of the magnification ratio of model 2 to model 1. The figure shows that the E–W reaction of model 2 is larger than that of model 1, and the maximum is approximately 1.4 times that in model 1. Especially in the area with the minimum modulus of the shallow sedimentary soil layer in the southern part of the basin, an extreme area with a displacement magnification of more than 2.2 times arises in the model 2 results. This extreme area arises because the average wave velocity and Young’s modulus of the first sedimentary layer (i.e., the shallowest Quaternary layer) in model 2 are slightly smaller than those in model 1 (the average wave velocity of the Quaternary unit in model 2 is 391 m/s and that in model 1 is 400 m/s). This result indicates that the E–W-trending earthquakes are sensitive to shallow structural
changes, which may be caused by the narrow E–W-trending structure of the Yuxi Basin. The N–S reaction of model 2 is less than that of model 1, and the minimum is only approximately 0.6 times that of model 1. The influence of the lateral heterogeneity in the sediments on the simulation results shows a normal distribution, which has the greatest influence on E–W earthquakes and has a certain influence on N–S earthquakes. The average E–W peak displacement ratio of each calculation node in the basin is 1.012, and the average N–S peak displacement ratio is 0.979. The average of three repetitions is 0.999, which shows that the two models are consistent in the overall amplification of ground motion. The refinement of the internal structure of the basin does not change the overall amplification trend of the basin in relation to the ground motion energy, but it does affect its distribution characteristics.

In Fig. 14, all the results on the ground are divided into 9 classes by the displacement ratio of the two models, i.e., 0.6–0.8, 0.8–0.9, 0.9–0.95, 0.95–0.98, 0.98–1.02, 1.02–1.05, 1.05–1.1, 1.1–1.2 and 1.2–1.4. The height of the bar indicates the proportion of a class relative to the total results. In Fig. 14,
(a) represents E–W, (b) represents N–S, (c) represents up and down (U–D), and (d) gives the horizontal average.

Table 3 shows the proportional distribution of the difference between the calculation results of model 2 and model 1. The table shows that for approximately 4% of the calculation points of the two models, the difference between the calculation results is more than 20%. As shown in Fig. 13, these differences are mainly located on the southern edge of the basin, which is the largest amplification area. In addition, for 46.69% of the calculation points, the difference between the two models is more than 5%. The difference in the horizontal ground motion obtained by averaging the N–S and E–W directions is small; however, in nearly one-third of the calculation points, the difference is more than 5%. The arithmetic average is used here rather than vector synthesis, which needs further analysis in practical applications. Overall, fine lateral modelling has a great impact on the simulation results.

5. Conclusions and Discussion

In this paper, a velocity model of six vertical layers of Tertiary and Quaternary sediments in the Yuxi Basin is constructed according to seismic reflection data. On this basis, the characteristics of the psephicity and particle size of sediments in multiple shallow borehole datasets are analysed, and a lateral zoning scheme of shallow Quaternary sediments based on the characteristics of the hydrodynamic sedimentary environment is given and is manifested as the difference in the shear wave velocity. A velocity model that depends on the lateral heterogeneity of sediments in the Yuxi Basin is constructed. This model can be used for various types of ground motion simulation calculations and analyses of site and basin effects.

The velocity model of the lateral heterogeneity of sedimentary strata in the Yuxi Basin is analysed by numerical simulation, and a detailed distribution map of seismic displacement magnification in the E–W and N–S directions of the Yuxi Basin is given. The map clearly shows the focusing and edge effects of the basin site. The extreme value of the displacement magnification in the E–W direction is more than 2 times the normal value, and the extreme value is not in the deepest area of the basin, which indicates the complexity of the basin effect.

The simulation results of the lateral heterogeneity of sediments are compared with those of the uniform distribution of the flat layer model. The overall magnification of the two models (the average value of all surface calculation points) is consistent, but the distribution of the focusing and edge effects changes. This displacement comparison does not show an obvious connection with the uneven lateral boundaries of shallow sedimentary layers, and the refinement of the model has a greater impact on the basin edge effect. For the E–W ground motion that has a large difference, in the region with the largest amplification factor, for approximately 4% of the calculation points, the difference between the calculation results of the two models is more than 20%, and the difference between nearly half of the calculation points is more than 5%. Fine lateral modelling greatly influences the simulation results. The accuracy of the velocity model is an important factor to be considered when using a high-precision numerical simulation method to analyse ground motion.
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**Declarations**

**Conflict of interest** The authors declare that they have no conflict of interest.

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**REFERENCES**

Daniel Roten, Yifeng Cui, Kim B. Olsen, et al. High-frequency nonlinear earthquake simulations on petascale heterogeneous supercomputers[C]. Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis, 2016, Article No.: 82:1–12.

Eduardo R (1999), Mario O. Spectra ratios for Mexico City from free-field recording. Earthquake Research, 119, 6421–6451.

Jachens, R. C., Sikora, R. F., Brabb, E. E., et al. (1997). The basement interface: San Francisco Bay area, California, 3-D seismic velocity model, EOS Trans. AGU, 78, F436.

Jachens, R C, C M Wentworth, D L Gautier, et al. 2001. 3D geologic maps and visualization: A new approach to the geology of the Santa Clara (Silicon) Valley, California, US. Geol. Surv. Open-File Rept, 01–223.

Jachens, R C, C M Wentworth, R W Simpson,et al. 2005. Three-dimensional geologic map of the Santa Clara Valley and adjacent uplands, California, Geol. Soc. Am, Cordilleran Section, 101st Annual Meeting.

Jinping Guo. 2016. Study on source rupture mode effects of near-field long period strong ground motion and its applications in Yunnan area. A Dissertation for Master Degree, Institute of Geophysics, China Earthquake Administration.

Kawase, H. (1996). The Cause of the Damage Belt in Kobe: “The Basin-Edge Effect”, Constructive Interference of the Direct S-Wave with the Basin-Induced Diffracted/Rayleigh Waves. *Seismological Research Letters.*, 67(5), 25–34.

Koketsu, K., Miyake, H., et al. (2009). A proposal for a standard procedure of modeling 3-D velocity structures and its application to the Tokyo metropolitan area, Japan. *Tectonophysics*, 472, 290–300.

Molinari, A. A., et al. (2015). Development and testing of a 3D seismic velocity model of the po plain sedimentary Basin, Italy. *Bulletin of the Seismological Society of America*, 105(2A), 753–764.

M. Peter Stuss and Shaw J H. 2003. P wave seismic velocity structure derived from sonic logs and industry reflection data in the Los Angeles basin, California. *Journal of Geophysical Research, 108(B3).*
Nobuyuki Yamada and Hiroaki Yamanaka. 1999. Comparison of performances of 3D subsurface structural models in the southwestern part of the Kanto Plain for strong motion simulation; examination using an earthquake (M JMA 4.1) in the west of Kanagawa Prefecture of May 22. Zisin, 2001, 53(4): 313–324.

Yamada, N., & Yamanaka, H. (2003). Ground motion simulations of moderate earthquakes for comparison of performance of 3D subsurface structural models in Kanto Plain for strong motion prediction. Zisin, 56(2), 111–123.

Pitarka, A., Graves, R. W., & Somerville, P. (2004). Validation of a 3D velocity model of the Puget sound region based on modeling ground motion from the 28 February 2001 Nisqually earthquake. Bull. Seism. Soc. Am., 94(5), 1670–1689.

Taborda, R., & Bielak, J. (2015). Ground-motion simulation and validation of the 2008 Chino Hills, California, Earthquake. Bulletin of the Seismological Society of America, 103(1), 131–156.

Hartzell, S., Harmsen, S., & Frankel, A. (2010). Effects of 3D random correlated velocity perturbations on predicted ground motions. Bulletin of the Seismological Society of America, 100(4), 1415–1426.

Takemura, S., Akatsu, M., et al. (2015). Long-period ground motions in a laterally inhomogeneous large sedimentary basin: Observations and model simulations of long-period surface waves in the northern Kanto Basin, Japan. Earth, Planets and Space, 67, 33.

Kagawa, T., Zhao, B., Miyakoshi, K., et al. (2004). Modeling of 3D basin structures for seismic wave simulations based on available information on the Target Area: Case Study of the Osaka Basin. Japan. Bull. Seism. Soc. Am., 94(4), 1353–1368.

Li, T., Chen, X., & Li, Z. (2021). Development of an MTF in ADINA and its application to the study of the Yuxi Basin effect. Journal of Seismology, 25, 683–695.

Imperatori, W., Gallović, F. (2017). Validation of 3D Velocity Models Using Earthquakes with Shallow Slip: Case Study of the 2014 Mw 6.0 South Napa, California, Event. Bulletin of the Seismological Society of America, 107(2):1019–1026.

Dhakal, Y. P., & Yamanaka, H. (2013). An evaluation of 3-D velocity models of the Kanto basin for long-period ground motion simulations. Journal of Seismology, 17, 1073–1102.