Analysis of strong ground motion characteristics recorded on reclaimed soil site

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Abstract. This paper discusses the difference between the strong ground motion of reclaimed soil sites and those of free-field ground motion. We determine under what conditions the influence of reclaimed soil can be ignored, and the ground motion on the reclaimed soil site can be regarded as a free field. Finite element models of reclaimed soil were constructed by analyzing the actual situation of strong ground motion observation on reclaim soil sites. Using a “lumped mass explicit dynamic finite element” method, the effects of shear wave velocity and thickness of reclaimed soil on free-field ground motion are analyzed. Replacing thicker reclaimed soil with remolded soil is proposed to reduce the impact of reclaimed soil sites on the ground motion of free field sites, the effects of which are analyzed by numerical simulation. Results show that the ground motion peak and the response spectra of the reclaimed soil site are significantly different from those of the free field site. With increasing reclaimed soil thickness, the influence is more noticeable. The impact of reclaimed soil on the free-field site can be reduced with reclaimed soil being replaced by remolding soil. The conclusions provide a theoretical basis for the rational use of strong ground motion records on the reclaimed soil site and the construction of strong motion stations.

1. Introduction
“Free-field” refers to strong ground motion on an open field that is not affected by the vibration of the surrounding environment and structure. According to the regulation “Specification for the construction of seismic station-strong motion station” (DB/T 17-2006) [1], strong motion stations should be built on free-field sites. Moreover, the “Technical Guideline for Construction of Earthquake Early Warning System” [2] regulation requires that site selection for early warning strong motion stations should be on free-field sites, and should avoid building on reclaimed soil and river beach sites, and nearby steep ridges and tall buildings. The aim is to obtain round motion recordings during a destructive earthquake to minimize the impact of local site condition, so as to effectively determine the seismic design parameters of the construction project.

However, in recent years, with the rapid development of China's economy, urban construction is expanding rapidly resulting in the erection of many buildings. Urban site conditions are, however, highly varied. This has caused a sharp decline in the number of free-field sites that meet requirements for the construction of strong motion stations, and some strong motion stations are built on reclaimed
soil sites. For example, because sites near high-speed railways, such as Beijing-Shanghai, Harbin-Dalian, Beijing-Shijiazhuang-Wuhan etc., used reclaimed soil, strong motion stations in the earthquake early warning (EEW) system of high-speed railways were difficulty selected a suitable site to meet the strong motion observation condition of free-field. The EEW strong motion stations could only be built on reclaimed soil sites, resulting in the corresponding construction sites not being the free-field sites required for the construction of strong motion stations. A study[33] showed that these conditions would impact strong ground motion.

This paper discusses the difference between the strong ground motion records of reclaimed soil sites and those of free-field ground motion. We determine under what conditions the influence of reclaimed soil can be ignored and ground motion of the reclaimed soil site can be regarded as that of a free field. Finite element models of reclaimed soil were constructed by analyzing the actual situation of strong ground motion observation on reclaim soil sites. Using a “lumped mass explicit dynamic finite element” method[4], the effects of shear wave velocity and thickness of reclaimed soil on free-field ground motion were analyzed. Replacing thicker reclaimed soil with remolded soil is proposed to reduce the impact of reclaimed soil sites on the ground motion of free field sites, the effects of which were analyzed by numerical simulation. The conclusions provide a theoretical basis for the rational use of strong ground motion records on the reclaimed soil site and the construction of strong motion stations.

2. Numerical simulation models and analysis method
Whether the strong ground motion obtained from reclaimed soil sites is free-field ground motion has not yet been determined by qualitative analysis. This issue will be qualitatively discussed by means of seismic response analysis. Seismic response analysis of reclaimed soil sites is a semi-space infinite domain problem, and it is necessary to introduce an artificial boundary to transform the infinite domain problem into a finite domain problem. Appropriate artificial boundary conditions are set to simulate outward scattering waves through the artificial boundary into the finite domain. The artificial boundary conditions used are the Multi-Transmitting Formula (MTF) proposed by Liao Zhenpeng[5]. MTF has a simple physical concept and is easy to realize time-space decoupling and precision controllable numerical simulation of wave motion combined with finite element or finite difference. For the seismic response in the finite domain, the lumped mass explicit time-domain dynamic finite element method was used. However, the seismic response on the artificial boundary was adopted using the MTF. The basic formula of the lumped-mass explicit time-domain dynamic finite element method, combined with MTF and its stable implementation measures, can be found in the literature[5-15]

3. Seismic response analysis on reclaimed soil sites
For strong motion stations built on reclaimed soil sites, the impact of the reclaimed soil can be determined by seismic response analysis. The artificial boundary is introduced to extract a calculation area of 50 m × 50 m × 30 m = 75000m³ from the elastic half space overlaid by reclaimed soil of a certain thickness. The top surface is a free surface, and the other sides and the bottom surface are artificial boundaries, as shown in figure 1. The model consists of two layers of media. The top layer is reclaimed soil of thickness, h, and the bottom layer is undisturbed soil. Model parameters and media are listed in table 1. Seven models were constructed based on the difference in reclaimed soil thickness and wave velocity. For the above-mentioned models, the calculation region is discretized into elements 0.5 m × 0.5 m × 0.5 m, and the size of the element is determined based on the calculation accuracy requirement of the dynamic finite element. The analysis model was solved by a lumped mass explicit dynamic finite element numerical simulation method combined with the MTF, and the calculation time-step Δt=0.0005s was determined by its stable calculation condition. The incident displacement pulse from bottom is shown in figure 2 and has width 0.2 s, duration 0.6 s, and amplitude 1 cm. The effective frequency band is 0-20 Hz, extracted from the Fourier spectrum of the pulse (as shown in figure 3) and covers band of engineering interest. The surface seismic response of the reclaimed sites and the corresponding response spectra are shown in figure 4 and figure 5.
Figure 1. Analysis model of reclaimed soil sites.

Figure 2. Input pulse.

Figure 3. Fourier spectrum of input pulse.

Table 1. Model parameters of reclaimed soil sites.

| Model | Thickness (m) | Shear wave velocity (m/s) | Poisson’s ratio | Damping ratio | Natural density (kg/m³) |
|-------|---------------|---------------------------|-----------------|---------------|------------------------|
| 1     | Undisturbed soil | 30                         | 200             | 0.30          | 0.05                   | 1850                   |
| 2     | Reclaimed soil      | 0                          | 0               | 0.30          | 0.05                   | 0                      |
| 3     | Undisturbed soil   | 28                         | 200             | 0.30          | 0.05                   | 1850                   |
| 4     | Reclaimed soil     | 2                          | 150             | 0.35          | 0.05                   | 1700                   |
| 5     | Undisturbed soil   | 28                         | 150             | 0.35          | 0.05                   | 1850                   |
| 6     | Reclaimed soil     | 8                          | 200             | 0.30          | 0.05                   | 1700                   |
| 7     | Undisturbed soil   | 30                         | 200             | 0.30          | 0.05                   | 1850                   |
| 8     | Reclaimed soil     | 8                          | 250             | 0.30          | 0.05                   | 1950                   |
| 9     | Undisturbed soil   | 25                         | 250             | 0.30          | 0.05                   | 1850                   |
| 10    | Reclaimed soil     | 5                          | 250             | 0.30          | 0.05                   | 1950                   |
| 11    | Undisturbed soil   | 8                          | 250             | 0.30          | 0.05                   | 1850                   |
| 12    | Reclaimed soil     | 22                         | 250             | 0.30          | 0.05                   | 1950                   |
Figure 4. Pulse response on backfill soil sites.

Figure 4(a) shows surface seismic responses when the shear wave velocity of the reclaimed soil is lower than that of the underlying undisturbed soil. The seismic response peak of the reclaimed soil site, of 2 m thickness (model 2), is similar to those of the free-field site (model 1), and the peak of the reclaimed soil sites gradually increases with increasing reclaimed soil thickness and delays. Figure 4(b) shows the surface seismic responses when the shear wave velocity of the reclaimed soil is higher than that of the underlying undisturbed soil. The seismic response peak of the reclaimed soil sites gradually decreases with increasing reclaimed soil thickness and advances.

In short, irrespective of whether the shear wave velocity of reclaimed soil is higher or lower than that of the underlying undisturbed soil, the effect on surface seismic response is remarkable, with increasing reclaim soil thickness. When the shear wave velocity of reclaimed soil is lower than that of the underlying undisturbed soil, the amplification effect of reclaimed soil is more noticeable, with increasing reclaimed soil thickness. When the shear wave velocity of the reclaimed soil is higher than that of the underlying undisturbed soil, the de-amplification effect of reclaimed soil is more noticeable, with increasing reclaimed soil thickness.

Figure 5. Ratios of seismic response spectra on reclaimed soil sites ratio to the free-field site.

Figure 5(a) shows the ratios of seismic response spectra of reclaimed soil sites to that of the free-field site, when the shear wave velocity of the reclaimed soil is lower than that of the underlying undisturbed soil. Figure 5(a) shows that the surface response spectra of the reclaimed soil site, of thickness 2m (model 2), are similar to those of the free-field site (model 1); and the influence of reclaimed soil on response spectra at below 2s is obvious, increasing with increasing reclaimed soil thickness. Figure 5(b) shows the ratios of seismic response spectra of reclaimed soil sites to that of the free-field site when the shear wave velocity of reclaimed soil is higher than that of the underlying undisturbed soil. Figure 5(b) shows that the influence of reclaimed soil on the response spectra at below 2s is obvious, decreasing with increasing reclaimed soil thickness. The response spectra of all analytical models show that the effect of reclaimed soil on the response spectra at over 2s is negligible.

In short, regardless of whether the shear wave velocity of reclaimed soil is higher or lower than that
of underlying undisturbed soil, its effect on the response spectra is frequency-dependent. The effect on response spectra is remarkable over the frequency band of 0.5Hz, but negligible in the other frequency bands.

4. Seismic response analysis of remolded soil sites

In view of the thickness of the reclaimed soil have a certain effect on the strong ground motion of free-field site, and the measure of replacing the reclaimed soil in a certain area with the remolded soil similar to the undisturbed soil was adopted to reduce the influence of reclaimed soil. However, a certain difference between the dynamic characteristics of remolded soil and those of undisturbed soil is inevitable. The impact of remolded soil can be determined using seismic response analysis of the remolded soil site. The seismic response analysis models of remolded soil are based on models of reclaimed soil, and reclaimed soil in a certain area is replaced by remolded soil, as shown in figure 6. The model consists of three kinds of media. The bottom is undisturbed, the top is reclaimed soil of thickness, h, and the center of the reclaimed soil has a remolded soil of volume2min length, 2m in width and h in depth. The thickness and mechanical parameters of reclaimed soil, undisturbed soil and remolded soil are shown in table 2. Nine models were constructed based on varying thickness and wave velocity of remolded soil. Based on models9 and 10, five models were constructed by changing the remolded soil plane size only. Model parameters are listed in table 2. According to the calculation accuracy requirements of the dynamic finite element, the discrete finite element of the calculation region is determined to be a 0.5 m × 0.5 m × 0.5 m cube. The lumped mass explicit dynamic finite element numerical simulation method combined with the MTF is used to solve the seismic response of remolded soil sites. The calculation step size Δt=0.0005s is determined using the stable calculation condition. A displacement pulse of 0.2 s in width, 0.6 s in duration, and 1 cm in amplitude was incident from the substrate (as shown in figure 3). The surface seismic response of the remolded soil and the corresponding response spectrum are shown in figure 7 and figure 8.

Figure 6. Analysis model of remolded soil.

Figure 7(a) shows the surface seismic responses when shear wave velocity of the remolded soil is equal to that of the underlying undisturbed soil. The seismic response peak of the remolded soil site, of 2 m thickness (model 8), is similar to those of the free-field site (model 1), and the peak of remolded soil sites gradually increases with increasing remolded soil thickness and delays. Figure 7(b) shows the surface seismic responses when the shear wave velocity of the remolded soil is lower than that of the underlying undisturbed soil. The seismic response peak of the remolded soil site, of 2 m thickness (model 11), is similar to those of the free-field site (model 1), and the peak of remolded soil sites increases gradually with increasing remolded soil thickness and delays. Figure 7(c) shows the surface seismic responses when the shear wave velocity of the remolded soil is lower than that of the underlying undisturbed soil. The seismic response peak of the remolded soil site, of 2 m thickness (model 14), is similar to those of the free-field site (model 1), and the peak of remolded soil sites increases gradually with increasing remolded soil thickness and delays. Figure 7(d) shows the surface seismic responses in the case of remodeled soil, of 5m thickness, and different plane sizes. The seismic response peak of the remolded soil columns, of different plane sizes, is larger than the that of the
free-field (model 1) and the peak of remolded soil sites gradually decreases with increasing plane size. Figure 7(e) shows the surface seismic responses when remodeled soil is of 8m thickness and different plane sizes. The seismic response peak of the remolded soil columns, with different plane sizes, is larger than that of the free-field (model 1), and the peak of the remolded soil sites gradually decreases with increasing plane size.

In short, regardless of whether the shear wave velocity of remodeled soil is equal to, higher than or lower than that of the underlying undisturbed soil, the effect on surface seismic response is remarkable, with increasing reclaimed soil thickness. The amplification effect of reclaimed soil becomes more noticeable as reclaimed soil thickness increases. In addition, the amplification effect of reclaimed soil gradually decreases with increasing remolded soil plane size. The amplification effect of reclaimed soil is negligible in practical engineering when the remolded soil plane size is larger than its thickness.

Table 2. Parameters of remolded soil site model.

| Model | Thickness (m) | Shear wave velocity (m/s) | Poisson’s ratio | Damping ratio | Plane size (m²) | Natural density (kg/m²) |
|-------|--------------|---------------------------|----------------|--------------|----------------|------------------------|
| Undisturbed soil | 30 | 200 | 0.30 | 0.05 | 50×50 | 1850 |
| Reclaimed soil | 0 | 0 | 0 | 0 | 0 | 0 |
| Remodeled soil | 0 | 0 | 0 | 0 | 0 | 0 |
| Undisturbed soil | 28 | 200 | 0.30 | 0.05 | 50×50 | 1850 |
| Reclaimed soil | 2 | 150 | 0.35 | 0.05 | 50×50 | 1750 |
| Remodeled soil | 2 | 200 | 0.30 | 0.05 | 2×2 | 1850 |
| Undisturbed soil | 25 | 200 | 0.30 | 0.05 | 50×50 | 1850 |
| Reclaimed soil | 5 | 150 | 0.35 | 0.05 | 50×50 | 1700 |
| Remodeled soil | 5 | 200 | 0.30 | 0.05 | 2×2 | 1850 |
| Undisturbed soil | 22 | 200 | 0.30 | 0.05 | 50×50 | 1850 |
| Reclaimed soil | 8 | 150 | 0.35 | 0.05 | 50×50 | 1700 |
| Remodeled soil | 8 | 200 | 0.30 | 0.05 | 2×2 | 1850 |
| Undisturbed soil | 28 | 200 | 0.30 | 0.05 | 50×50 | 1850 |
| Reclaimed soil | 2 | 150 | 0.35 | 0.05 | 50×50 | 1700 |
| Remodeled soil | 2 | 180 | 0.30 | 0.05 | 2×2 | 1800 |
| Undisturbed soil | 25 | 200 | 0.30 | 0.05 | 50×50 | 1850 |
| Reclaimed soil | 5 | 150 | 0.35 | 0.05 | 50×50 | 1700 |
| Remodeled soil | 5 | 180 | 0.30 | 0.05 | 2×2 | 1800 |
| Undisturbed soil | 22 | 200 | 0.30 | 0.05 | 50×50 | 1850 |
| Reclaimed soil | 8 | 150 | 0.35 | 0.05 | 50×50 | 1700 |
| Remodeled soil | 8 | 180 | 0.30 | 0.05 | 2×2 | 1800 |
| Undisturbed soil | 28 | 200 | 0.30 | 0.05 | 50×50 | 1850 |
Figure 7. Pulse response on remolded soil.

Figure 8(a) shows the ratios of seismic response spectra from remolded soil sites to those of the free-field site when the shear wave velocity of remolded soil is equal to that of the underlying undisturbed soil. Figure 8(a) shows that surface response spectra of the remolded soil site, of 2 m thickness (model 8), are similar to those of the free-field site (model 1), and the influence of remolded
soil on the response spectra at below 2s is obvious, increasing with increasing remodeled soil thickness. The effect of remodeled soil on the response spectra at over 2s is negligible. Figure 8(b) shows the ratios of seismic response spectra on remodeled soil sites to those of the free-field site when the shear wave velocity of remodeled soil is lower than that of the underlying undisturbed soil. Figure 8(b) shows that the surface response spectra on the remodeled soil site, of 2 m thickness (model 11), are similar to those of the free-field site (model 1), and the influence of remodeled soil on response spectra at below 2s is obvious, increasing with increasing remolded soil thickness. The effect of remolded soil on the response spectra at over 2s is negligible. Figure 8(c) shows the ratios of seismic response spectra of remolded soil sites to those of the free-field site when the shear wave velocity of remolded soil is larger than that of the underlying undisturbed soil. Surface response spectra of the remolded soil site, of 2 m thickness (model 14) are similar to those of the free-field site (model 1). The influence of remolded soil on response spectra at below 2s is obvious, increasing with increasing remolded soil thickness, while the influence of remolded soil on response spectra at over 2s is negligible.

Figure 8. Ratios of seismic response spectra on remolded soil sites to the free-field site. Figure 8(d) shows the ratios of seismic response spectra of remolded soil sites to those of the
free-field site when the remolded soil is of 5m thickness, with different plane sizes. Figure 8(d) shows that the influence of remolded soil on response spectra at below 2s is obvious, decreasing with increasing plane size of remolded soil, while the influence of remolded soil on response spectra at over 2s is negligible. Figure 8(e) shows the ratios of seismic response spectra of remolded soil sites to those of the free-field site when the remodeled soil is 8m thick, with different plane sizes. The influence of remolded soil on response spectra at below 2s is obvious, decreasing with increasing plane size of remolded soil, while the effect of remolded soil on response spectra at over 2s is negligible.

In short, regardless of whether the shear wave velocity of remodeled soil is equal to, higher than or lower than that of the underlying undisturbed soil, the effect on surface response spectra is frequency-dependent. The effect on response spectra is remarkable over a 0.5 Hz frequency band, but negligible over other frequency bands. In addition, the influence of reclaimed soil on response spectra gradually decreases with increasing plane size of remolded soil. The influence of reclaimed soil on response spectra is negligible in practical engineering when remolded soil plane size is larger than its thickness.

5. Conclusion
Finite element models were constructed by analyzing real site conditions of strong ground motion observations on reclaimed soil sites. Based on the numerical simulation method of lumped mass explicit dynamic finite element, the effect of the shear wave velocity and the thickness of reclaimed soil on free-field ground motion were analyzed. For thicker reclaimed soil sites, replacing reclaimed soil with remolded soil was proposed to reduce the impact of reclaimed soil on ground motion of free-field sites, the effectiveness of which was analyzed by numerical simulation. The main conclusions based on the numerical simulation are summarized as follows:

1) The effects of reclaimed soil on the surface seismic response are remarkable, with increasing reclaimed soil thickness. When the shear wave velocity of the reclaimed soil is lower than that of the underlying undisturbed soil, the amplification effect of reclaimed soil sites is more noticeable with increasing reclaimed soil thickness. When the shear wave velocity of the reclaimed soil is higher than that of the underlying undisturbed soil, the de-amplification effect of reclaimed soil is more noticeable with increasing reclaimed soil thickness. In addition, the effect of reclaimed soil on the response spectra is frequency-dependent. The effect on response spectra is remarkable over a frequency band of 0.5Hz, but negligible over other frequency bands.

2) Replacing reclaimed soil within a certain area with remolded soil, similar to undisturbed soil, can reduce the influence of reclaimed soil. The influence of reclaimed soil is obviously reduced with the increase of the remolded soil region. The influence of reclaimed soil is negligible in practical engineering when the remolded soil plane size is larger than the thickness of reclaimed soil.

In summary, for a strong motion station built on a reclaimed soil site, replacing the reclaimed soil with remolded soil can reduce the influence of the reclaimed soil on strong ground motion. If the replacement area is large enough, the site can be regarded as a free-field site. This paper provides a theoretical basis for the rational use of strong ground motion records of reclaimed soil sites, and the construction of strong motion stations.

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