A NON-UNIFORM INPUT MOTION CALCULATION METHODOLOGY FOR HIGH CONCRETE FACE ROCKFILL DAMS

Yu YAO¹, Rui WANG², Tianyun LIU³, Jian-Min ZHANG⁴

ABSTRACT

A new method is developed in this study to determine the potential functions of the seismic waves in the near field based on seismic records, and applied in the seismic analysis of high CFRDs under non-uniform input motion. As an example, the acceleration time histories recorded during the 2011 Tohoku earthquake at the Haga station is used to determine the potential functions of the seismic waves, which is then used to conduct simulations on the seismic response of the Gushui CFRD under uniform and non-uniform input motion. Under the condition that the acceleration time histories on the surface of the free field are assumed to be consistent for both non-uniform and uniform seismic input the seismic response of the CFRD under non-uniform input is found to be significantly smaller, while the dynamic tensile stress around the edges of the concrete face slab is greater. The simulation results suggest that non-uniformity of the ground motion input has important effects on the seismic response of high CFRDs, and should be considered in the seismic design of CFRDs.

Keywords: Seismic waves; Potential functions; Non-uniform input; High CFRDs; Seismic response

1. INTRODUCTION

The ground motion input is necessary in the seismic design of concrete face rockfill dams (CFRD). Currently, most design codes and guidelines assume the input ground motion to be uniform in the seismic evaluation of CFRDs (e.g. ICOLD Bulletin 120, 2001). In fact, because of the traveling wave effect and the site effect, the phenomenon of non-uniform ground motion is very obvious for high CFRDs. In China, quite a number of high CFRDs are being built or will be built, and most of them are located in meizoseismal areas, such as Gushui (the maximum height is 245 m, the fortification intensity is Ⅷ), Cihaxia (the maximum height is 253 m, the fortification intensity is Ⅷ), Maji (the maximum height is 277.5 m, the fortification intensity is Ⅷ), etc. So there is an urgent need to study the seismic response of CFRDs subjected to non-uniform ground motion input.

The non-uniform input methods based on wave theory take the irregularity of the ground surface into account, which are suitable for the application to high CFRDs. There exist several aforementioned methods, including the finite element method (FEM) or the finite difference method (FDM) with all kinds of local artificial boundaries, for instance, the viscous boundary (Lysmer and Kulemeyer, 1969), the visco-elastic boundary (Deeks and Randolph, 1994) and the transmitting boundary (Liao et al., 1984); and methods to solve the global wave field equations, for instance, the boundary element method (BEM) (Hall, 1994), the scaled boundary finite element method (SBFEM) (Song and Wolf, 1997), the wave function expansion method (WFEM) (Sanchez-Sesma et al., 1985), the Green function method (GFM) (Wong, 1982), and the wave function combination method (WFCM) (Yao et

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al., 2016). All of these methods need to determine the incident waves, which at present are usually obtained by statistic methods. A coherency model for the wave propagation based on existing earthquake records is used (e.g. Dibaj and Penzien, 1969; Shen and Xu, 1983; Tian, 2003). For better description of spatial variability, some researchers have further developed models for the propagation of seismic waves from the source to the ground surface (e.g. Zerva et al., 1986; Beck, 1979). However, the existing earthquake records are already effected by the scattering of the ground surface, which cannot be taken into account by such models. To solve this problem, a new methodology is proposed in this paper to determine the potential functions of the seismic waves in the near field based on actual seismic records in section 2 of this paper. In section 3, the acceleration time histories recorded during the 2011 Tohoku earthquake at the Haga station is used to determine the potential functions of the seismic waves for instance. In section 4, the responses of the Gushui CFRD on Lancang River subjected to those seismic waves are analyzed for modes of uniform and non-uniform input, and the characteristics of the response of high CFRDs subjected to non-uniform input is analyzed by the comparison with the uniform input case.

2. METHOD TO DETERMINE INCIDENT WAVES

A method of undetermined coefficients is used to determine the incident waves. It is assumed that all of the incident waves are propagated from the same earthquake focus, and consist of P waves, S waves and Rayleigh waves.

First we need to assume the incident angles of waves. Based on the refraction law, the angle of refraction is depend on the velocity of the waves. Therefore the incident angles we need to assume are limited to five parameters, which are the horizontal azimuth angle of P waves $\theta_P^{h}$, the vertical azimuth angle of P waves $\theta_P^{v}$, the horizontal azimuth angle of S waves $\theta_S^{h}$, the vertical azimuth angle of S waves $\theta_S^{v}$, and the horizontal azimuth angle of Rayleigh waves $\theta_R^{h}$. The maximum range of the horizontal azimuth angle is from 0 degree to 360 degrees, and the maximum range of the vertical azimuth angle is from 0 degree to 90 degrees. When solving a practical problem, the position of the epicenter is known, and the angle between the horizontal direction of incidence and the line from the epicenter to the site is within 90 degrees in general, thus limiting the range of the horizontal azimuth angle to 180 degrees.

When the incident angles are assumed, we need to determine the potential functions of P waves, SV waves, SH waves and Rayleigh waves in frequency domain, denoted as $\varphi_P$, $\varphi_{SV}$, $\varphi_{SH}$ and $\varphi_R$. Through the selected non-uniform input method based on wave theory, the acceleration of any recording spot in frequency domain can be expressed as

$$\omega^2 \cdot \begin{bmatrix} U_{p1} & U_{SV1} & U_{SH1} & U_{R1} \\ U_{p2} & U_{SV2} & U_{SH2} & U_{R2} \\ U_{p3} & U_{SV3} & U_{SH3} & U_{R3} \end{bmatrix} \begin{bmatrix} \varphi_P \\ \varphi_{SV} \\ \varphi_{SH} \\ \varphi_R \end{bmatrix} = \begin{bmatrix} \ddot{a}_u \\ \ddot{a}_v \\ \ddot{a}_h \end{bmatrix} \quad (1)$$

where $\omega$ is the circular frequency; $U$ stands for the displacement generated by the unit potential function in frequency domain corresponding to $\omega$, of which the subscripts stand for the type of the wave, the direction, and the number of the recording spot, respectively; $\ddot{a}$ stands for the recorded acceleration transformed to frequency domain corresponding to $\omega$, of which the subscripts stand for the direction and the number of the recording spot, respectively. If there are two recording spots or more, equation (1) will be an overdetermined equation, and a least square solution can be obtained. The relative error of the least square solution can be defined as
\[ ERR_j = \frac{\|A - \hat{A}\|}{\|\hat{A}\|} \]  

(2)

where \( A \) is a matrix which consists of the acceleration time history for three directions calculated by the least square solution, i.e.

\[
A = \begin{bmatrix} a_{x1} & a_{y1} & a_{z1} \\
\end{bmatrix}
\]  

(3)

and \( \hat{A} \) is a matrix which consists of the recorded acceleration time history for three directions, i.e.

\[
\hat{A} = \begin{bmatrix} \hat{a}_{x1} & \hat{a}_{y1} & \hat{a}_{z1} \\
\end{bmatrix}
\]  

(4)

When conducting the proposed method, the horizontal azimuth angle and the vertical azimuth angle could be assumed within their ranges at equal intervals. The combination of incident angles corresponding to the smallest \( ERR_j \) is taken as the actual incident angles, and the corresponding least square solution is taken as the coefficients of potential functions, thus the incident waves are determined. To improve the accuracy, we can also assume some angles at smaller intervals around the determined incident angles to obtain a smaller \( ERR_j \). Besides, other unclear parameters, such as the Young's modulus of the site can also be conducted as the incident angles.

3. Example to Conduct the Method

The acceleration time histories recorded during the 2011 Tohoku earthquake at the Haga station (National Research Institute for Earth Science and Disaster Prevention website, 2015) are used to conduct the proposed method as an example. The records include the acceleration time histories of the point at the surface of the ground and the point 112m underground (Figure 1).
The topography around the Haga station is flat, as shown in Figure 2. Thus we can regard the site as a half space. For simplicity, the half space is assumed as an isotropic elastic media, of which the Poisson’s ratio is set as 0.22 and the density is set as $2700 \text{kg/m}^3$. Further assume that the Poisson’s ratio remains a constant in the propagation of the waves from the earthquake focus to the site, thus the refractive index is the same for P waves and S waves, deducing that the horizontal azimuth angle are the same for different kind of incident waves and the vertical azimuth angle are the same for different kind of incident body waves (P and S waves). Since the Young’s modulus of the site is also unclear, the parameters to be assumed including the horizontal azimuth angle of incident waves $\theta_1$, the vertical azimuth angle of incident body waves $\theta_2$, and the Young’s modulus of the site $E$.  

Figure 1. Acceleration time histories of the point at the surface of the ground and the point 112m underground in the east-west (EW), north-south (NS), and vertical (UD) directions.
The earthquake focus is located at 142.860 degrees east longitude, 38.103 degrees north latitude, and the Haga station is located at 140.075 degrees east longitude, 36.548 degrees north latitude. Define the horizontal azimuth angle of the east direction as 0 degree and the counterclockwise direction is positive, it can be calculated that the horizontal azimuth angle of the direction from the epicenter to the station is 215 degrees. Define the vertical azimuth angle of the incident wave as the angle between the incident direction and the vertical upward direction. Then change $\theta_1$ around 215 degrees at an interval of 30 degrees, change $\theta_2$ from 0 degrees to 70 degrees at an interval of 10 degrees, change $E$ from 4GPa to 24GPa at an interval of 2GPa. For each combination of assumed parameters, use the proposed method to determine the incident waves. The relative error $ERR$ is shown in Figure 3. It can be seen that when $\theta_1$ equals to 155 degrees, $\theta_2$ equals to 40 degrees and $E$ equals to 6GPa the relative error $ERR$ reaches its minimum value 0.293. The corresponding least square solution is taken as the coefficients of potential functions, thus the incident waves are determined.
Figure 3. The relative error $\text{ERR}_r$ for different $\theta_1$, $\theta_2$ and $E$

4. DYNAMIC ANALYSIS OF GUSHUI CFRD

The Gushui CFRD is located on Lancang River. The seismic precautionary intensity of the dam is 8 degrees, and the peak value of the design basic acceleration of ground motion is $2.81\text{m/s}^2$. The maximum height, length and width of the dam is 245m, 710.6m and 396m, respectively. The direction of the dam axis is $23^\circ 48'$ from south to east. The upstream water depth is 228m. The acceleration records of the Haga staion from the 110 second to the 130 second are used after a coefficient is multiplied by to convert the peak value of the ground acceleration to that of the design basic acceleration of ground motion.

Figure 4 shows the finite element mesh of the dam, which consists of 10729 nodes and 10318 hexahedron elements. The concrete face slab, the crest and the wave wall are modeled as linear elastic, with Young’s modulus of 30GPa and Poisson's ratio of 0.167. The densities of them are set as $2400\text{kg/m}^3$. The Duncan-change E-B model is adopted for the constitutive model of the rockfill in the static analysis, in which the parameters for the rockfill material of the CFRD are listed in Table 1. An equivalent visco-elastic model proposed by Shen (Shen and Xu, 1996), which has accumulated much application experience in the design and analysis of rockfill dams in China over the past three decades,
is adopted in this study for the constitutive model of the rockfill in the dynamic analysis. The parameters used in the dynamic and residual deformation analysis for the rockfill material of the CFRD are listed in Table 1.

![Finite element mesh of Gushui CFRD](image)

**Figure 4. The finite element mesh of Gushui CFRD**

<table>
<thead>
<tr>
<th>Material</th>
<th>$c$ (kPa)</th>
<th>$\phi$ (°)</th>
<th>$k$</th>
<th>$K_{ur}$</th>
<th>$n$</th>
<th>$R_f$</th>
<th>$K_b$</th>
<th>$m$</th>
<th>$\Delta \phi$ (°)</th>
<th>$\rho$ (kg/m$^3$)</th>
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<tr>
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<td>54.4</td>
<td>1200</td>
<td>1800</td>
<td>0.3</td>
<td>0.75</td>
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<td>0.15</td>
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<td>53.5</td>
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<td>1875</td>
<td>0.31</td>
<td>0.78</td>
<td>720</td>
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<td>1350</td>
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<td>0.28</td>
<td>0.8</td>
<td>780</td>
<td>0.18</td>
<td>11.3</td>
<td>2214</td>
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<tr>
<td>Secondary rockfill zone</td>
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<td>53</td>
<td>1350</td>
<td>2025</td>
<td>0.28</td>
<td>0.8</td>
<td>780</td>
<td>0.18</td>
<td>11.3</td>
<td>2214</td>
</tr>
<tr>
<td>Cushion zone</td>
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<td>55</td>
<td>1300</td>
<td>1950</td>
<td>0.31</td>
<td>0.79</td>
<td>800</td>
<td>0.12</td>
<td>12.2</td>
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<table>
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<tr>
<th>Material</th>
<th>$k_2$</th>
<th>$\lambda_{max}$</th>
<th>$\mu_d$</th>
<th>$k_1$</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$c_3$</th>
<th>$c_4$</th>
<th>$c_5$</th>
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<tbody>
<tr>
<td>Cushion zone</td>
<td>3223</td>
<td>0.16</td>
<td>0.2</td>
<td>40</td>
<td>0.455</td>
<td>0.0145</td>
<td>0.97</td>
<td>0</td>
<td>0.0491</td>
</tr>
<tr>
<td>Transition zone</td>
<td>3828</td>
<td>0.24</td>
<td>0.2</td>
<td>42</td>
<td>0.345</td>
<td>0.0145</td>
<td>0.97</td>
<td>0</td>
<td>0.0491</td>
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<td>Main rockfill zone</td>
<td>2660</td>
<td>0.21</td>
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<td>0.444</td>
<td>0.0084</td>
<td>0.81</td>
<td>0</td>
<td>0.1082</td>
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<tr>
<td>Secondary rockfill zone</td>
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<td>0.2</td>
<td>39</td>
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<td>0.0084</td>
<td>1.62</td>
<td>0</td>
<td>0.1082</td>
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<tr>
<td>Drainage zone</td>
<td>3223</td>
<td>0.16</td>
<td>0.2</td>
<td>40</td>
<td>0.455</td>
<td>0.0145</td>
<td>0.97</td>
<td>0</td>
<td>0.0491</td>
</tr>
</tbody>
</table>

Both the non-uniform and the uniform seismic input are used for the dynamic analysis. For non-uniform input, the incident waves determined in Section 3 are used after the period of time and the magnitude are modified as aforementioned. For uniform input, the modified records of the surface point of the Haga station are used. Figure 5 (a) and (b) show the contours of the peak acceleration along the river on the cross section in the middle of the dam for non-uniform input and uniform input, respectively. It can be observed that the peak acceleration under non-uniform ground motion input is
overall smaller. Figure 6 (a) and (b) show the contours of the peak dynamic compressive stress perpendicular to the dam slope within the concrete face slab under uniform and non-uniform input, respectively. In similar fashion, Figure 7 (a) and (b) show the contours of the corresponding peak dynamic tensile stress. Under non-uniform input, both the compressive and the tensile stress perpendicular to the dam slope within the concrete face slab are in general smaller, which is to be expected considering the difference in the acceleration of the CFRD. However, Figure 6 (c) and Figure 7 (c) show the difference of the peak dynamic stress of the face slab between the non-uniform input case and the uniform input case, it can be seen that around the edges of the concrete face slab, the stress of the concrete face slab under non-uniform input is greater. This increase of stress under non-uniform input could be caused by the phase and amplitude difference between the input motions at different positions. The difference in stress due to non-uniform input motion should be considered in design as a potential threat to the safety of the seepage control system, as such locations are weak links of the seepage control system where failures are exceptionally detrimental and difficult to repair.

Figure 8 (a) and (b) show the residual settlement contours on the cross section in the middle of the dam for non-uniform input and uniform input, respectively. Similar to the acceleration results, the residual settlement under non-uniform input is smaller than that under a comparable uniform input.

Figure 5. Peak acceleration along the river (m/s²)
Figure 6. Peak dynamic compressive stress perpendicular to the dam slope (MPa)
Figure 7. Peak dynamic compressive stress perpendicular to the dam slope (MPa)
Table 3 shows the maximum peak acceleration along the river, peak dynamic compressive and tensile stress of the concrete face, and post-earthquake compressive and tensile stress of the concrete face. The acceleration along the river exhibits as much as 58% relative difference between non-uniform and uniform, while all other results showed around 10% to 45% relative differences. These results indicate that current design and analysis approaches of using uniform input could result in seismic responses that deviate significantly from reality, and the design for high CFRDs based on non-uniform input is necessary. It can be seen that under the conditions of study in this paper, the dynamic response and residual deformation induced by uniform input is in general larger than those induced by non-uniform input, suggesting current design and analysis methods to be conservative. However, the stress results shown in Figure 6(c) and Figure 7(c) also suggest that the seismic response obtained under uniform input is not globally conservative, where the dynamic stress around the edges of the concrete face slab could be larger under non-uniform input compared with that under uniform input. The greater dynamic stress at the edges could provide explanations for some of the damage observed by Zhang et al. near the abutment of the Zipingpu CFRD after the Wenchuan earthquake (Zhang, 2015).
Table 3. The peak response of the dam under uniform input and non-uniform input

<table>
<thead>
<tr>
<th>Items</th>
<th>Uniform input</th>
<th>Non-uniform input</th>
<th>Percentage of the difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_y$ (m/s$^2$)</td>
<td>14.12</td>
<td>5.93</td>
<td>58%</td>
</tr>
<tr>
<td>s(m)</td>
<td>0.51</td>
<td>0.45</td>
<td>12%</td>
</tr>
<tr>
<td>$\sigma_{ds}$ (MPa)</td>
<td>-8.94</td>
<td>-7.59</td>
<td>15%</td>
</tr>
<tr>
<td>$\sigma_{dp}$ (MPa)</td>
<td>10.57</td>
<td>9.41</td>
<td>11%</td>
</tr>
<tr>
<td>$\sigma_{dt}$ (MPa)</td>
<td>-10.06</td>
<td>-7.06</td>
<td>30%</td>
</tr>
<tr>
<td>$\sigma_{dp}$ (MPa)</td>
<td>12.29</td>
<td>7.04</td>
<td>43%</td>
</tr>
<tr>
<td>$\sigma_{pa}$ (MPa)</td>
<td>-2.29</td>
<td>-1.42</td>
<td>38%</td>
</tr>
<tr>
<td>$\sigma_{pp}$ (MPa)</td>
<td>15.30</td>
<td>10.98</td>
<td>28%</td>
</tr>
<tr>
<td>$\sigma_{pt}$ (MPa)</td>
<td>-3.66</td>
<td>-2.40</td>
<td>34%</td>
</tr>
<tr>
<td>$\sigma_{ps}$ (MPa)</td>
<td>11.70</td>
<td>8.27</td>
<td>29%</td>
</tr>
</tbody>
</table>

Note: $a_y$ - Acceleration along the river
s - Residual settlement
$\sigma_{ds}$ - Dynamic tensile stress of the face along the axis of the dam
$\sigma_{dp}$ - Dynamic pressure stress of the face along the axis of the dam
$\sigma_{dt}$ - Dynamic tensile stress of the face along the slope of the face
$\sigma_{dp}$ - Dynamic pressure stress of the face along the slope of the face
$\sigma_{pa}$ - Post-earthquake tensile stress of the face along the axis of the dam
$\sigma_{pp}$ - Post-earthquake pressure stress of the face along the axis of the dam
$\sigma_{pt}$ - Post-earthquake tensile stress of the face along the slope of the face
$\sigma_{ps}$ - Post-earthquake pressure stress of the face along the slope of the face

5. CONCLUSIONS

A new method is developed in this study to determine the potential functions of the seismic waves in the near field based on seismic records, which can take the scattering of the ground surface into account for a better description of spatial variability. This method is conducted to determine the incident waves around the Haga station during the 2011 Tohoku earthquake, and the result is used for the dynamic analysis of Gushui CFRD.

The dynamic analysis for Gushui CFRD shows that when the acceleration at the surface of the free field for dynamic simulations with uniform and non-uniform input are kept consistent, the response of CFRDs under non-uniform input is in general significantly smaller, suggesting current design and analysis methods to be conservative. However, the dynamic stress around the edges of the concrete face slab could be larger under non-uniform input compared with that under uniform input, and pose non-negligible threat to the seepage control system.

The dynamic constitutive model for the rockfill area is a simple nonlinear model. In future studies, high fidelity plasticity constitutive models should be adopted. Wave scattering problem solutions that are able to take into consideration non-uniform bedrock should also be developed. It should also be noted that the non-uniform input motion calculation method is developed under the assumption that the bedrock is a homogeneous isotropic linear elastic medium, and the modulus is much larger than that of the rockfill dam.
6. ACKNOWLEDGMENTS

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7. REFERENCES


