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Wang, John G. Z. Q., "Ground Waving and Its Damaging Effect" (1993). *International Conference on Case Histories in Geotechnical Engineering*. 10.
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Proceedings: Third International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, June 1-4, 1993, Paper No. 3.28

Ground Waving and its Damaging Effect

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SYNOPSIS Some unusual patterns of earthquake damages due to ground waving have been described in order to draw attention to further research towards these problems. A brief introduction of relevant theoretical approach to torsional components of ground motion and amplification of seismic surface waves due to local topographic irregularities have been given in this paper to provide a contrast between theoretical approach and practical cases in order to reflect the gap to be filled.

INTRODUCTION

Through numerous investigations over the damaged areas of strong earthquakes,many seemingly unbelievable but really happened unusual patterns of destruction have been found. Among them, ground waving is the most significant one.The author prefers this terminology as it can properly describe the real behavior of ground movement during strong earthquakes where permanent deformation of the ground surface just reveals waving forms ever occurred. People in the field during some strong earthquakes(e.g.Xingtai,March 22,1966,M=7.2) did ever experience watchable waving of ground just like the patterns left permanently in the field.

The mechanism and geometric figures of structural damages caused by ground waving seem to be so amazing that they can hardly be checked with the current methodology of seismic design.Conventionally,seismic force specificly acting on a structure is visualized as the product of the mass of the structure times the seismic acceleration. However,this is not applicable to ground waving damages as shown in the following for example.

TORSIONAL GROUND WAVING

An illustrative example(Tangshan earthquake M=7.8, 1976) is given in Fig.1 showing that the rails were damaged in unusual manner by overwhelming ground movement which exhibits very clear surface wave form--horizontally rotational Love wave. In Fig.2,a vertically rocking motion can be seen as a Rayleigh wave.

These damages make great sense illustrating the rails were distorted not directly by seismic force acting on them,because their mass is too small to exert seismic inertial force big enough to destroy the rails. It is obvious that the rails were fixed on the sleepers which weremainly embedded in the stone crashes of the roadbed. Therefore,they were actually fixed on the ground and thus deformed totally together with ground waving. Insitu measurement proved that the distorted rails appeared to be shorter in wave length than that of Love wave and Rayleigh wave respectively. This may be due to the coupled vibration with a compound rigidity of both rail and ground soil.

BRIEF REVIEW OF TORSIONAL MOTION

In recent years,theoretical approach to seismic rotational motion has been made by many researchers.

Niazi(1982) first obtained an inferred rotational motion using decomposed traveling waves from a 3-D accelerogram of a strong motion array at El Centro during Imperial Valley earthquake in 1979.

Trifunac(1982) carried out systematic research on both translational and rotational components of seismic ground motion by inducing body wave into elastic half-space. Lee and Trifunac(1985) further developed synthetic torsional accelerogram from translational data.

Oliveira and Bolt(1989) estimated rotational components of seismic waves by using densified strong motion array SMART-1 in Taiwan and arrived at a conclusion that when Curl $u > 0.0001$rad,significant effects of rotational components on engineered structures generally appear.

Wang(1983) conceptually proved that whenever dipping interface exists between overburden and underlying layer,and shear wave velocity of the former is smaller than the latter,rotational motion on the ground should occur.

Recent advances in this aspect were made by Boffi and Castellani(1991),Jin and Liao(1991). The latter developed synthetic design rotational and rocking components with synthetic translational Fourier spectra for a known source with given magnitude M and epicentral distance Δ .

It is advisable to synthesize torsional components based on traveling wave in the elastic

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homogeneous layered half-space in which the rotational displacement vector at nth layer is

$$\Omega_n(x_1,x_2,t) = \frac{1}{2}\left(\frac{\partial u_{3(n)}}{\partial x_2}\vec{x}_1 - \frac{\partial u_{3(n)}}{\partial x_1}\vec{x}_2\right) \qquad (1)$$

$$= \Omega_{1(n)}(x_1,x_2,t)\vec{x}_1 + \Omega_{2(n)}(x_1,x_2,t)\vec{x}_2 \qquad (2)$$

where $\vec{x}_1$, $\vec{x}_2$ are the unit vectors along X_1 (horizontal), X_2 (vertical) axes respectively; u_3 is the displacement of a point in nth layer along X_3-axis; and

$$\Omega_{1(n)} = \frac{1}{2\rho_n V_{s(n)}^2}\tau_{2,3(n)} \qquad (3)$$

$$\Omega_{2(n)} = \frac{i\omega}{2c(\omega)}u_{3(n)} \qquad (4)$$

where ρ_n is the mass density; $V_{s(n)}$ is the shear wave velocity of the nth layer; $\tau_{2,3(n)}$ is the shear stress on X_2, X_3 (X_3 is horizontal and normal to the paper) plane; $c(\omega)$ is the phase velocity along X_1 axis.

Equation (3) and (4) demonstrate that when shear wave polarizes through an interface, it will result in two torsional motions: one is torsion around horizontal axis X_1 which is directly proportional to the shear stress; the other is a rotation which is subject to the out-of-plane displacement. Since there is no stress on the free surface of the soil ground, equation (4) is the only expression for the rotational motion of Love wave.

Therefore, the rotational acceleration of Love wave in terms of Fourier spectrum $\phi_2(\omega)$ can be obtained from the out-of-plane acceleration Fourier spectrum $a_3(\omega)$, i.e,

$$\phi_2(\omega) = \frac{i\omega}{2c(\omega)}a_3(\omega) \qquad (5)$$

For vertically rocking of Rayleigh wave induced by P-SV incident waves, two translational components and three torsional components in the nth layer of the elastic half-space are:

$$\left.\begin{aligned} u_{1(n)} &= \frac{\partial\phi_{(n)}}{\partial x_1} + \frac{\partial\psi_{(n)}}{\partial x_2} \\ u_{2(n)} &= \frac{\partial\phi_{(n)}}{\partial x_2} - \frac{\partial\psi_{(n)}}{\partial x_1} \\ \Omega_{1(n)} &= 0 \\ \Omega_{2(n)} &= 0 \\ \Omega_{3(n)} &= -\frac{1}{2}\nabla^2\psi_{(n)} \end{aligned}\right] \qquad (6)$$

where $\phi_{(n)}$, $\psi_{(n)}$ are scalar potential function and vector potential function of nth layer respectively. And $\psi_{(n)}$ satisfies the wave equation, thus

$$\Omega_{3(n)} = \frac{\omega^2}{2V_{s(n)}^2}\psi_{(n)} \qquad (7)$$

Similarly, the Fourier spectrum $\phi_3(\omega)$ of vertical rocking acceleration around axis X_3 on the ground can be obtained from the Fourier spectrum $a_2(\omega)$ of translational acceleration along axis X_2 :

$$\phi_3(\omega) = \frac{\omega}{ic(\omega)}a_2(\omega) \qquad (8)$$

Thus, by inverse transformation of Fourier spectra in equations (5) and (8), the time histories of both rotational acceleration $\phi_2(t)$ and rocking acceleration $\phi_3(t)$ can be obtained for aseismic design.

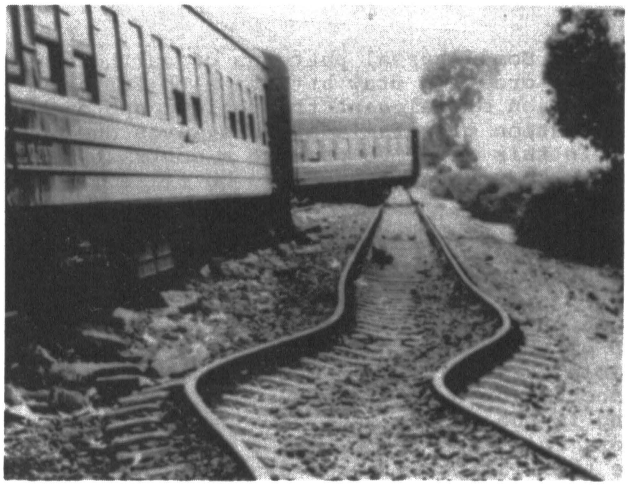

Fig.1 Rails and coaches rotated purely horizontally due to Love wave (Tangshan event M=7.8,1976)

Fig.2 Rails rocked purely vertically due to Rayleigh wave action (Tangshan event M=7.8,1976)

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EXISTING PROBLEMS IN TORSIONAL GROUND MOTION ANALYSIS

The existing methodologies for analysing torsional components of ground motion are theoretically right. However,there are still many questionable points left unsolved in engineering practise:

A. It can hardly be realized why the most destructive and irresistible torsional damages only occurred at certain specific sites where either purely rotational movement only or rocking movement only was locally intensified.

B. Strong motion array records are very rare and the instrumentation is too expensive to meet the need of a particular site.

C. Using synthetic rotational and rocking components seems to be realistic only when there are enough strong motion records to provide statistical data of amplitude and phase spectra. The inferred source parameters(M,L--fault length,h--focal depth) are also difficult to be precisely predicted for a particular site. The angle of incidence which affects the horizontal apparent wave velocity is hard to be pre-estimated .

D. In the vicinity of surface faulting,rotational ground movement may occur.Its mechanism follows that of the faulting which is still not thoroughly explored.

E. Other than the normally induced torsional components,many additional factors e.g. diffraction and scattering of surface wave due to topographic irregularities or structural changes may result in locally intensified motion which cannot be counted in analytically at the same time.

STATIONARY WAVE DESTRUCTION

When seismic wave travels within a confined area like river channel,small lake or a basin,reflected secondary waves will be induced and propagate back and forth within the limited boundaries.Eventually, as the progressing wave and reflected wave coinside in equal phase,magnified amplification will take place at all the peaks and remain standing for a certain duration.

Fig.3 is one of the highway bridges in Tangshan area totally damaged in the manner of throwing over and overlapping of the reinforced concrete slab girders in longitudinal direction without any transverse(river stream direction) displacement at all. This pattern of damage is a very representative one of the river bridges of small and medium size destroyed in high intensity zone.

A striking contrast can be seen in Fig.3 that a group of single storey long span masonry warehouse just closely behind the wholly collapsed small bridge,stands still without major damage.It appears to be non-resonant damage because there wasn't much difference between their frequencies. And stationary wave action is the understandable cause.

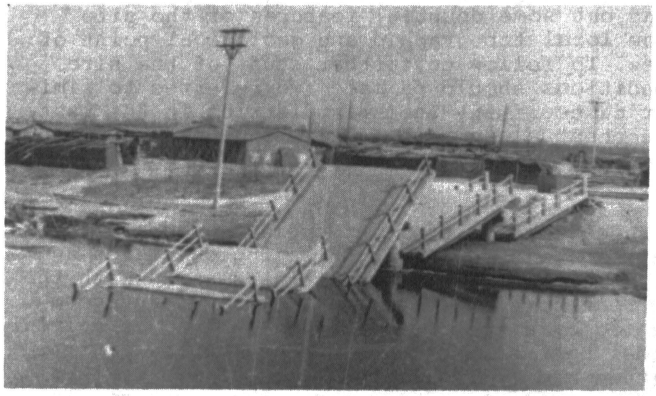

Fig.3 Plate girders of highway bridge thrown and overlapped longitudinally whereas nearby warehuoses stood still

Theoretically,stationary wave may take place when the group velocity of a surface seismic wave packet coincides with that of the overburden layer. Take the conditional equation of Love wave for example,let v_1 ,v_2 represent the horizontal displacements above and below the interface along Y-axis,we have

$$V_2\sqrt{1-\frac{V_L^2}{V_{S(2)}^2}}=V_1\sqrt{\frac{V_L^2}{V_{S(1)}^2}-1}\cdot \mathrm{tg}[\frac{\omega h}{V_L}\sqrt{\frac{V_L^2}{V_{S(1)}^2}-1} \qquad (9)$$

where $V_{S(1)}$, $V_{S(2)}$ are shear wave velocities of the overburden and the half-space respectively. V_L is the velocity of Love wave.

Obviously equation(9) exists only when $V_{S(1)} < V_L < V_{S(2)}$. Due to dispersion of seismic wave,V_L varies with frequency or wave length. As the wave number k ($=\omega / V_L$) is large enough and wave length becomes so small that $V_L \rightarrow V_{S(1)}$,the magnified stationary Love wave will occur.

Dravinski and Trifunac(1979) summarized from the research on SH and Love waves in a homogeneous, isotropic,linear and elastic layered medium that the contribution of locally standing waves to the total energy density spectrum is significant within the thickness of the top layer.

However,stationary wave destruction cases are extremely specific in terms of local topographic and geological features which can hardly be analytically formulated for prediction.In fact, the propagation of seismic surface waves in many cases is a very complicate combination and additive action of diffracted,scattered and reflected waves in layered strata resulting in an overwhelming waving.

PRACTICAL MEASURES SUGGESTED FOR SITING

In view of the current state of this problem, the following points are suggested for siting with particular attention to ground waving damages.

-In the reconstruction of an earthquake damaged area,it is resonably advisable that any project to be rebuilt on the same locality which was severely damaged ever before by ground waving, should be further restricted,because this sort of seismic destruction is actually irresistible and likely to recur in the next strong event no matter what source mechanism will be.

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- For siting in a virgin land where no relevant information available at all, a well experienced earthquake-geotechnical engineer may be able to find out some doubtful features of the site from local topographic and geological point of view. To follow up, further study of the site conditions should be made and referred to similar cases if any in other district in the past. A conceptual and substantial presumption can be made based on a detail comparison between the two.

- In case very important project proposed to be built on a site of ground waving suspicion and less information, theoretical assessmentwith the current torsional component methodology accompanied by a model test in the lab may be helpful. Model test should be run under the law of similitude and follow the criteria of similarity. Proper excitation of seismic input may result in an illustrative collateral evidence.

CONCLUSION

Severe earthquake damages caused by ground waving during a strong event are so far irresistible and unsolved in aseismic design especially for linear structures on ground surface, like rail road, highway bridges and pipelines etc. Before this problem has been thoroughly solved theoretically, some practical measures for siting in strong earthquake zones may help prevent from such disastrous hazards.

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