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A SIMPLIFIED REASONING OF RIGIDITY EFFECT OF FOUNDATION SOIL ON SEISMIC DAMAGE TO BUILDING

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ABSTRACT

The rigidity effect of soil layer on earthquake damage to buildings is delineated in a simple manner by accounting for the different types of earthquake source, wave propagation, as well as the variations of soils' and buildings' conditions.

KEYWORDS

Soil rigidity; earthquake source; wave propagation; building damage; soil-structure interaction.

INTRODUCTION

A great number of field observations in past earthquakes worldwide and ground response analyses have indicated that the rigidity of foundation soil has vital effect on the extent of damage to buildings, under the same seismic environment. Currently, the dominant conception is that soft soils would be more unfavorable than hard soils, attributing the reason to a larger ground deformation amplification. However, there are also some reverse situation indicating that there exist many other factors influencing the building damages. These factors include the different features and quantities of earthquake source, wave propagation statue, soil properties, stratification, geologic structure, and building specific variable. Though so far there were considerable amount of the data and literature relevant to these topics, it yet cannot say with enough confidence that the exact truth and rigorous statement were known by us regarding such a tremendous complicated natural phenomenon occasionally occurred below the deep ground of the secret Earth by a unforesighted force at unpredicted time. Among the variety of factors we may conclude the following four to be more important, namely, (1) The mechanism of earthquake source; (2) Ways of wave propagation; (3) Amplification and filteration (deamplification) of rock and soil layers; and (4) Characters and behaviors of buildings, including soil-building interaction. In this paper we intend to present some viewpoints based on some simplified reasoning without the use of complicated mathematics and detailed computations but, to the utmost, with primary physical insight.

EFFECT OF THE MECHANISM OF EARTHQUAKE SOURCE ON BASE INPUT

It is evident that the mechanism of earthquake source must have prime influence to building damages though they are a long distance apart. It seems that using only the magnitude and epicentral distance as well as an empirical attenuation law may not capture the total feature of the base excitation to soil layers. We are of the opinion that the mechanism of quake source definitely specifies the disturbing pattern to deep ground while the geological structure influences additionally the wave propagation pattern to various layer boundaries, including the ground surface. Apart from tectonic explanations we rather intuitively make some illustrations on the basis of principles of Mechanics henceforth.

Boundary and Initial Conditions at Source

From the principles of Mechanics, the boundary condition and initial condition must be specified at first to solve a concrete problem and obtain its unique complete solution. Therefore, at the earthquake source what those conditions just, for example, at the start of fault break and then on the fault plane are should be known clearly, since they strongly influence the solution of their consequence. For solid mechanics problems one type of boundary condition, given stress or given displacement, is sufficient on a free boundary surface (for mixed boundary problem given stress on part of the surface and given displacement on other part of the surface). From viewpoint of Mechanics, the tectonic processes in the Earth are very slow and at the source area of earthquake, either collision and subduction zones of interplate motion, or elastic rebound zones of intraplate motion, a suddenly intensive break occurrence must imply that the excessive stress is the main cause but not the displacement which must slowly develop before the break started. Such a break causes a instantaneous stress drop in company with the break propagation to the whole fault plane, while an unloading wave propagates from the source to long distance away. Thus the initial condition may be of the form:

$\sigma_{\bar{r}} = \sigma_{st}\ (\mathrm{t}=0)$

$\dot{\mathrm{u}}_{\bar{r}} = \dot{u}_{st} \approx 0\ (t=0),\ \bar{u}_r = 0\ (t=0)$

while the boundary condition will be

$\sigma_0 = -\sigma_{sd}\delta(t)\delta(r) + \sigma_{res}\delta(r)$

where $-\sigma_{sd}$ – stress drop commonly of order $2 \times 10 \sim 2 \times 10^2$ bar=2 ~ 20Mpa

$\delta()$ – Dirac delta function

σ_{st} – initial stress before earthquake

σ_{res} – residual stress on fault plane

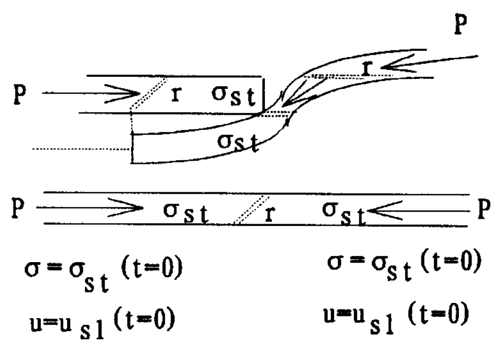

Fig. 1

Two Types of Soil Base Excitation

In addition to the very important factor of tectonic force types such as shearing, tension-compression, torsion, and bending or folding etc., which decide what kind of stress and deformation will play the principal part for that particular quake, we put emphasis herein only on two types of bedrock excitation.

1. For intraplate earthquake or other similar earthquake with simpler tectonic structure under simple tension or shearing, an unloading stress wave starts to propagate soon as the breaking starts to spread. Because a dislocation spread speed of 2-3 km/sec was estimated by Trifunac (1974, 1989), we may regard, approximately, the break as an instantaneous for the far fields. As unloading waves propagate with elastic wave speed which for bedrock may be of order 2-3 km/sec in shear and 4-6 km/sec in compression

(Finn,1995), so the disturbances at the source may propagate through bedrock with a velocity ratio about 4-10 to the overlying soil layers. It can be noted thus that stress waves in bedrock are much more fast than those in soil layers and we, therefore, can consider the whole bedrock moves in one same phase and gives an excitation to the overlying soils as an commonly considered one-dimensional problem. In this case the unloading stress waves are the original ones, while to simplify, we may consider it be under a displacement excitation on soils base for every particular location.

2. For interplate earthquake and other earthquake with complicated tectonic structure in the source area, an unloading elastic stress wave may also starts to propagate from the break zone firstly, but some secondary complicated collisions and breaking between the broken blocks and plates and their neighbors may cause additional loading stress and displacement waves which are elastic-plastic in nature and generally with a lower propagation speed than the unloading elastic waves. These might make a more complicated secondary wave motions and a longer duration. Consequently, the base excitations would be more complicated, dependent on many conditions, than those for intraplate earthquake. Since this type of earthquake, usually, would be stronger and made slip trace evidence even in upper soil layers (Ye, 1995), so the base excitations of bedrock can not always identify as simple as a displacement excitation, due to the existence of unloading and loading elastic-plastic waves interaction in bedrock and soil strata.

As an simplified example, Fig. 2 shows a situation of newly broken plate layer A and upper old broken layer B with a gap distance Δ.

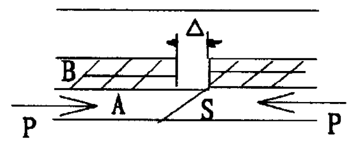

Fig. 2

Once layer A suddenly slipped across a fault plane S under the thrusting force P a unloading elastic shear wave will emit firstly and secondary loading compressional and shear waves will emit soon after the two branches of B are collided. As to the reaction of overlying soil layers it depends on many factors including the magnitude, the types of driving force, soil thickness, soil properties, and many others. In summary, we are intending to evoke attention that earthquake source types and features are one vital origin of building damages regardless the geometrical and soil material dampings as well as multiple wave defraction, scattering etc. through the complex geological paths. Because bedrocks show quite different mechanical behavior under loading and unloading stages, especially for cyclic loading condition, and of the much different geologic structures there will be many different types of earthquake excitations in reality that can not be described by the attenuation laws so far specified, which only taken account of the epicentral distance and magnitude. The late well-known Prof. LI Shi-guang (1977) had pointed out that "they are close for two points located in a tectonic unit although with long distance while they will be far apart in different tectonic units although with short distance", which correctly described one aspect of the drawback of the empirical attenuation laws.

WAVE PROPAGATION

Wave propagation in ground during earthquakes, both observational and theoretical, have extensive publications in the literature. However, an absolutely majority of them was based on the elastic wave theory. As we have pointed out above that the elastic wave theory was valid only for earthquake of simple unloading ruptures, whereas for quakes of complex unloading and loading and/or reloading only the precursor or the initial motion may exactly follow the elastic theory. So to distinguish carefully the following differences would be of significance before we deal with building damages problem.

1. Zone of disturbance. There may be the plastic and the elastic zone whose size and location are related to the source mechanism, magnitude, source depth, geologic structures etc.. Generally, a strong quake would cause a large plastic and elastic zone, with large deformation, stress and lower wave speed in plastic zone.

Within and near the area of the plastic zone the ground motion would be greater while the duration time and the wave period longer in contrast with the elastic zone.

2. Geometrical and material damping. As the source area is limited in size so the intensity of earthquake should be decreased with increasing epicentral distance. However, this geometrical damping effect may not be easy to evaluate definitely due to the fact that the much complicated tectonic structure, layering, interlocking and interaction among broken rock blocks, ingomogeneity, anisotropy, fissure and fracture planes in rocks, etc. must strongly and randomly-like influence this general trend, so that the so-called anomaly emergence somewhere in some direction does not mean anomaly but really a certain one. In other words, without a fully grasp of these detailed situation which is just the case to our knowledge, what we can do only is the use of empirical attenuation laws but need an awareness of their short-comings.

Material damping plays also a significant role to attenuate the wave propagation in the ground, which is also complicated in nature and needs much more work to thoroughly understand it. Usually, it depends on many factors such as rock and soil classification, straining condition, and stress level etc.. In many cases it was assumed as a viscous damping to simplify the solution in vibration and wave propagation.

3. Displacement wave and stress wave. For a pure elastic body, the one-dimensional wave equation is of same form for the stresses and their corresponding displacement components which means the stress and strain, and thus displacement propagate in same phase. However, after taking account of viscous damping, for instance, the stress wave and displacement wave will not be in phase but have a phase difference. So the stress do not reach their peak value when the displacements do. This fact would be of significance for the evaluation of base excitation to buildings as we will discuss in the following sections.

Ricker (1981) has studied the Kelvin-Voigt type of viscoelastic body and the wave propagation which is governed by Stokes equation . He used Hermite functions to construct the solution in form of an infinite series of wavelet polynomials. It was evident that there were differences of wave form and phase angle between the displacements and stresses waves.

AMPLIFICATION AND FILITERATION THROUGH ROCK AND SOIL LAYERS

It is well known that original seismic waves may suffer amplification and filiteration as they propagate away through the overlaid rock and/or soil layers, mainly due to the inhomogeneity of media especially the existence of discontinuous interfaces and the dissipative properties of media, not to say the irregular geological structure and topographical irregularity. So far, extensive efforts have made to study these problems and remarkable progress was achieved (Bard, 1994), in what follows we only mention some points that will be closely related to building damages.

1. Fundamental period of soil profile. As this period plays a major part to ground motion and building vibration, especially their resonance, so it is a very important index, for a site-specific seismic evaluation. There have been many exact and simplified procedures to estimating the period of single and multiple layered soils profile (Dobry, 1976) under linear or equivalent-linear behavior assumption.

2. Amplifications and filiterations of waves. Amplifications and filiterations depend mainly on the soils and rock impedance and their interaction behavior, soil damping and thickness of each layer for a horizontally layered soil system.

Recently, Aseismic Code provisions on soil site categories of some countries consider soil site become poorer with increasing thickness of soil deposits, which seemed to have not sound basis as we think that firstly, the effect of thickness is affected by a tangent function, and secondly, the damping effect should be increased with increasing of thickness which has been evidenced especially in medium to dense sands empirically. The unique unfavorable effect of thick layer may be the resonance for those buildings with very long self vibration periods.

BUILDING'S CHARACTER AND BEHAVIOR

It is obvious that the damage's extent to buildings will also much owe to building's self characters such as globe and local stiffness, strength, plan and sectional arrangement, shape, size, height over span ratio, structure type, foundation type, working years ect.. In particular, importance deserved to attribute to local weak zones or elements such as wall element between windows in brick buildings, quality of construction, and deteriorations of building behavior under static loading lifetime. Therefore, it can be imagined that the damages extent of a shaken building would be a complicated function of much more its own character and variables besides the influence of the source mechanism, wave propagation statue, and soil site effects, which thus should be investigated on one-by-one basis. Unfortunately, the current knowledge standard is not sufficient to make such examination for every buildings. In the following we only attempt to discuss some general aspects while put some unsolved yet problems aside at moment.

1. Resonance and Source Mechanism

So far, building-subsoil resonance induced damages are well recognized in the professionals worldwide, but we think of an additional type of resonance may be even important. This is the shaken rock-oversoil resonance. I other words, the overlaid soil will shake very strongly for some types of source's plate motion which likewise induce a shaken rock-oversoil resonance. Whenever, building-subsoil-shaken rock three units resonance occurred it would be the most dangerous case for buildings and ground motion. As these three units all are of multiple self natural frequencies so they have much possibility of resonance though with different possible decaying peak values. In this regard, we convince that the interplate and other lager earthquake with loading plastic and elastic waves and most complicated geologic structure, overlaid by thicker and softer (but in certain suitable range) soil deposits which are the site of buildings of larger self period might be the unfavorable combination, whereas the intraplate and other medium and small earthquake with mainly unloading waves and quite simple geologic structure, overlaid by thinner and stiffer (but in certain suitable range) soil deposits which are the site of buildings of shorter self period might be another unfavorable combination for resonance. These may explain why the damages are different for the same building, site condition, overlying soil deposits, magnitude and epicentral distance, but with different shaken mechanism (including initial and boundary condition at the source, and detailed structure of shake generated rock strata).

2. Soil Deposits' Condition

To simplify the discussion, we are limited here only to the horizontally layered soil deposits because to take account of topographic and subsurface irregularities must render much complexity to deal with something that so far likely not yet understood completely.

As is well known, for elastic soil assumption, a single layered soil deposit makes amplification of displacement and of stress at ground surface be approximately (Bard, 1994; Finn, 1995) $A_u = \frac{2\rho_R C_R}{\rho_S C_S}$ and $A_\sigma = \frac{2\rho_S C_S}{\rho_R C_R}$ where ρ —density, C—wave speed, subscripts R,S denote rock and soil respectively; subscripts u, σ denote displacement and stress, respectively. For multi-layered deposits the amplification will be more complicated and depended on the order of deposition, ρ ,C, and thickness of each layer. A general tendency is softer soils make displacements amplify and stresses deamplify and vice versa, under a same bedrock excitation.

Taking into consideration of soil nonlinearity, the solution becomes more complex regardless minor studies for some particular cases and so far has not yet completely obtained but a roughly tendency that it makes amplification to some lower extent and resonant frequency smaller. In what follows we consider only the linear cases.

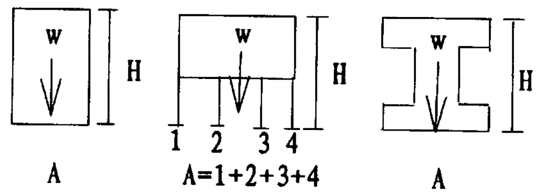

Fig. 3

3. Building Response

Seismic response of building located on soil deposits relates to the rigidity (stiffness) of soil and of building. The effect of building-soil interaction will decrease with increasing stiffness of soils (Young, 1994). Usually, to neglect this interaction effect may lead to a conservative result except something on resonance issue. So we use a simplified soil-building interaction model by regarding the building as an equivalent soil layer to evaluate its gross response below (The detailed responses of structural elements need more detailed analyses by FEM for instance). Assuming that a building of height H, total load (dead plus live) W, actual foundation base area A is rested on the ground surface. Its equivalent stiffness is characterized by two parameters $\bar{\rho}$ and $\bar{C}$ (or $\bar{G}$), whose determination (ref. Fig. 3) will be not difficult and thus not given herein. Note here we treated the building as the one-dimensional, not considering the outside free ground., which only cause some more error to subsoils than to building. Moreover, A influences stress τ but not displacement d, transmitted into building. Once seismic waves arrive at the foundation base, reflection and transmission waves are produced in soils and the equivalent building. For elastic soils and building under normal incidence waves, the most interested wave is the transmitted one which has been given (Men and Cui 1995) in form of transmission coefficient w_u and w_σ for displacement waves and stress waves, respectively. For single layer case they equal

$$w_u = \frac{2}{1 + i\dfrac{\rho_s C_s}{\bar{\rho}\bar{C}}\dfrac{1}{\tan\dfrac{\omega}{\bar{C}}H}}, \quad w_\sigma = \frac{2}{1 - i\dfrac{\bar{\rho}\bar{C}}{\rho_s C_s}\tan\dfrac{\omega}{\bar{C}}H}$$

when a harmonic plane wave of frequency ω inputs from soil media of $\rho_s C_s$. The larger w, the larger seismic loading (displ. or stress) to building will be. However, soil media exhibit viscous damping and the stress and strain (thus displacement too) have phase shift whereas the building was assumed elastic and has not such shift. As on the contact interface of soil-building two continuity conditions, i.e. displacements and stresses, must hold, so it seems that a displacement wave and a stress wave are consequently transmitted from soils to the building, and they would cause different building behaviors for different structure types, i.e. for instance, stress-sensitive or displacement-sensitive ones.

SOIL RIGIDITY TO BUILDING DAMAGE

Now, let us see the effect of soil rigidity on building damages, based on those statements in foregoing sections. It has been noted that because too many complicated factors influence the building damages in near fields, we will limit our discussion only on buildings in far fields in what follows.

1. Damage Due To Resonance

Higher soil rigidity makes heavier damages to buildings of high stiffness when their self frequencies nearly coincide, and vice versa, provided the quake mechanism enabling bedrock-soil layers resonance to be possible.

2. Damages Due To Wave (De)amplification And Existence Of Building

Since buildings are excited from the contact surfaces with subsoils so the boundary conditions on these surfaces would be of importance. Usually, for infinitesimal strain problems, two conditions will hold, i.e. stress and displacement continuity conditions while for large strain problems, only the stress continuity condition holds and the displacement does not always hold because of possible slip occurrence.

On the other hand, stresses become smaller and displacements become larger when these waves incident from stiffer media to softer ones, and vice versa. Therefore, we may conclude that

A. Stiffer building on softer ground (viz. $\frac{\overline{\rho C}}{\rho_s C_s} \rangle\rangle 1$)

Stress continuity condition holds.
Stresses in building become larger than in softer soil.

Upper bound $\tau_b \infty \frac{\overline{\rho C}}{\rho_s C_s}[\tau_y]$ or $= [\tau_b]$, where $[\tau_y]$ — yield stress of soil, $[\tau_b]$— yield stress of building.

Displacement continuity condition may or may not hold, approximately dependent on kW smaller or larger than fW, where k — seismic coefficient, f — friction coefficient between building foundation base and subsoil (including lateral soil resistance for densely buried foundation).

Displacement of building become smaller than in soft soil when kW<fW. Upper bound $d_b \infty |d_b| + |d_s|$ when kW>fW where d_b — building displacement due to friction slip under inertial forces, d_s — soil input displacement on the contact surface. Stress-sensitive light and weak structure with larger specific foundation area ratio, and small displacement-sensitive structure are unfavorable.

B. Softer building on stiffer ground (viz. $\frac{\overline{\rho C}}{\rho_s C_s} \langle\langle 1$)

Stress continuity condition holds.
Stresses in building become smaller than in stiffer ground.

Upper bound $\tau_b \infty \frac{\overline{\rho C}}{\rho_s C_s}[\tau_y]$ or $= [\tau_b]$

Displacement continuity condition holds when kW<fW or not holds when kW>fW. Displacement in building become larger than in stiffer ground . Displacement-sensitive structures and stress-sensitive light and weak structure with larger foundation area ratio are unfavorable.

C. Softer building on softer ground and stiffer building on stiffer ground

No evident amplification of stress and displacement will appear and damages are mainly due to resonance.

CONCLUSIONS

In the above simplified reasoning we rendered the problem seemingly too simple, however, the general tendencies might be referable to some believable extent. In summary, of particular importance would be the following points, viz.

1. The source mechanism plays key role to exert loading on soils firstly and then on building, which so far has been too oversimplified because of its complicated nature.

2. Soil properties and soil stratification statue are one major but not the most important influencing factor, as damage extent still relates to building's and the quake source's characters.

3. Building's damages associated with site soil conditions depend yet prominently on building's own conditions, including even the ratio of foundation area over total plan area, not to say rigidity distribution, weakness in resistance, stress or displacement sensitive, total weight, loading condition, natural periods, quality of construction, etc.. Therefore, one can not make a clear conclusion on what the effect of soil rigidity on building damages will be when no full knowledge is well grasped of source mechanism; ways of wave propagation; geologic structure, irregular geometrical surfaces and/or interfaces, discontinuities, anisotropy; and the quantitative characters, detailed conditions of each specific building etc.. It seems to be applicable here also a philosophical principle saying "do concrete analysis for concrete situation".

In addition, we are of the opinion that Rayleigh waves might be the most dangerous driving force for many buildings because of their simultaneous actions of vertical and horizontal displacement components. Limited by space we will discuss further elsewhere.

REFERENCES

Bard, P.Y., (1984). Effect of surface geology on ground motion: Recent results and remaining issues. Proc. 10th ECEE, vol. 1, 305-323.

Dobry, R. et al (1976). Simplified procedures for estimating the fundamental period of a soil profile. Bull. Seism. Soc. Amer., 66, 1293-1321.

Finn, W.D. and Ventura C. E. (1995). Challenging issues in local microzonation. Proc. 5 ICSZ, vol II, 1554-1561.

Li, Shi-Guang (1977). On Earthquake (in Chinese). Geology Press.

MEN, Fu-lu and CUI, Jie (1995). Effect of alternate dry and saturated soil layers on ground motion and wave propagation. Acta Geophysica Sinica, 38, 774-787.

Richker, N.H. (1981). Transient Waves in Visco-elastic Media (translated into Chinese). Geological Press.

TokuJi Utsu (1987). Dictionary of Major Things Related to Earthquake (in Japanese), Asamasa Press.

Trifunac, M.D. (1994). Earthquake source variables for scaling spectral and temporal characteristics of strong ground motion. Proc. 10th ECEE, vol.4, 2585-2590.

Ye Hong et al (1995). Study on the intraplate potential seismic sources. Proc. 5 ICSZ, vol.II, 1424-1430.

Yong, R.J. and Wong, S.M.P. (1994). Studies into the relationship between soil shear wave velocity and significance of SSI effects. Proc. 10th ECEE, vol. 1, 635-637.