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ROBUSTNESS OF PREDOMINANT DIRECTION OF NEAR-SOURCE GROUND MOTIONS AND ITS UTILIZATION IN PORT PLANNING

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A countermeasure against near-source ground motions should be established based on careful examinations of their characteristics. Since a tendency has been found for the strike-normal component to be predominant in the near-source region of a large intra-plate earthquake, it is expected to be a reasonable decision to orient important quay walls perpendicular to the strike of the active fault of concern. For the purpose of validating this decision, two kinds of analysis are conducted, namely, ground motion simulations to show the effects of fault parameters on the predominant direction of near-source ground motions and non-linear FEM analyses to show the effects of quay wall orientation on its residual deformation.

Key Words : *near-source ground motion, predominant direction, fault, quay wall, port planning*

1. INTRODUCTION

A countermeasure against near-source ground motions should be established based on careful examinations of their characteristics. Attentions should be paid to the fact that their characteristics are, in general, quite dependent on the source parameters. For example, amplitudes and predominant periods depend on the source parameters such as the slip velocity, the size of asperity and the rupture starting point, which cannot necessarily be predicted precisely with our current state of knowledge. On the other hand, the predominant direction of near-source ground motions seems to have a rather robust nature.

Somerville et al.[1)] examined near-source ground motion records from 21 earthquakes, most of which occurred in California, and found a presence of systematically larger ground motions in the strike-normal direction than in the strike-parallel direction close to faults at periods longer than 0.6 seconds. Takemura et al. [2)] reviewed the direction of simple body overturning and wooden house and chimney collapsing for 9 destructive shallow intra-plate earthquakes in Japan and found a tendency for the strike-normal component to be predominant in the near-source region.

Besides these empirical studies, an intuitive explanation for the predominant direction of near-source ground motions has also been established[1),3)]. In case of an ideal strike-slip fault, a superposition of SH waves radiated successively from each source element produces a large-amplitude pulse-like ground motion, which is polarized to strike-normal direction. In case of a thrust fault, a similar phenomena occurs but SV wave, instead of SH wave, radiated from each element produces a large-amplitude pulse-like ground motion, which is initially polarized in the fault-normal direction (not necessarily parallel to the ground surface) but, due to the gradual change in the incident angle, finally polarized in the strike-normal direction (parallel to the ground surface) when it arrives at the ground surface.

On the assumptions of the robustness of the predominant direction of near-source ground motions, it is expected to be a reasonable decision, in the port planning, to orient important quay walls that are constructed in the vicinity of an active fault perpendicular to the strike of the fault as long as the fault is well defined (**Fig.1**).

The author will present two kinds of analysis that were conducted for the purpose of validating the above decision. One of them concerns the effects of

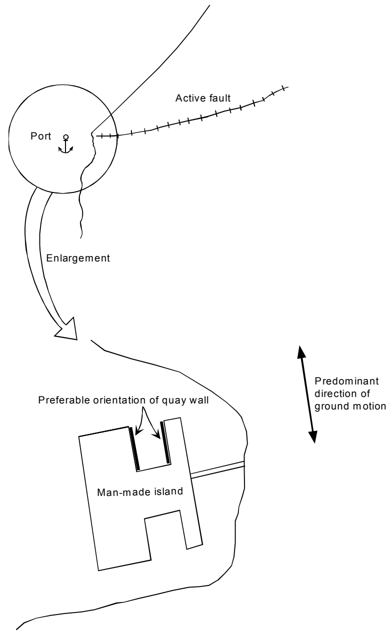

Fig.1 Preferable orientation of important quay walls.

Table 1 Underground structure model[5].

Thickness (m)	Vp (m/s)	Qp	Vs (m/s)	Qs	Density (ton/m³)
200	1600	200	350	20	1.7
300	1800	200	550	35	1.8
500	2500	350	1000	70	2.1
∞	5400	1000	3200	120	2.7

source parameters on the predominant direction of near-source ground motions and the other analysis concerns the effects of quay wall orientation on its residual deformation.

The former analysis was conducted because, in the foregoing intuitive explanation of the predominant direction of near-source ground motions, the earthquake is assumed to be either an ideal strike-slip earthquake or an ideal dip-slip earthquake. Actual earthquakes are more or less a mixture of these two extreme types of earthquake. For such cases, foregoing intuitive explanations does not necessarily apply and therefore some alternative theoretical background is needed to validate the robustness of the predominant direction. For this reason, a seismology-originated method was used to simulate near-source ground motions for a variety of combinations of dip and rake angles.

The necessity for the latter analysis arise from the fact that the response of a quay wall to ground motions is a quite complicated phenomena and its residual deformation cannot be easily related to ground motion parameters such as PGA or PGV. Non-linear finite element analysis is, although time consuming, currently the best way to show the effects of quay wall orientation on its residual deformation.

2. GROUND MOTION SIMULATIONS

(1) Method

Ground motions are simulated by superposing analytical Green's functions for a layered half-space[4]. The underground structure model listed in **Table 1** is used for the simulation. This structure represents a typical structure of sedimentary basin in Japan and is the same as that used by Kagawa and Ejiri[5]. Since a layered half-space model is employed, the effect of horizontal heterogeneity of the underground structure is omitted in the simulation. The contribution of waves due to horizontal heterogeneity, however, hardly exceeds that of direct S-wave in the near-source region. Even in the vicinity of a basin edge in Kobe, the contribution of edge waves to the generation of damage belt in Kobe is estimated to be 50% of that of direct-S wave[6]. The simulation is restricted to the frequencies lower than 2Hz because it is prohibitive to apply theoretical ground motion simulations to higher frequencies and because higher frequencies do not have significant effects on the residual deformation of quay walls[7]. Although the effects of horizontal heterogeneity is out of the scope of the present article, Harada et al.[8] showed that the strike-normal component is predominant for the case of a strike-slip fault near a sedimentary basin.

(2) Source parameters

Among various source parameters, a special attention is paid to the effects of the source mechanism, that is, the combination of dip and rake angles. Although the effects of other parameters such as the depth of asperity, the size of asperity and the rise time are also investigated, it was confirmed that these parameters do not have significant effects on the predominant direction of near-source ground motions.

As for the source mechanism, 8 combinations of dip and rake angles are assumed as listed in **Table 2** and as indicated in **Fig.2**. In **Fig.2**, the source mechanisms identified for (the subevents of) the shallow intra-plate earthquakes with magnitude of 7 or larger in the 20th century in Japan are also plotted[9]. Although many of the earthquakes are either of pure strike-slip type (group A) or of pure dip-slip type (group B), some earthquakes fall between them. The mechanisms assumed in the simulations (solid rectangles) are selected to cover the range of

Table 2 Combinations of dip and rake angles.

Dip (degree)	90	80	70	60	30	40	50	60
Rake (degree)	0	30	60	90	90	60	30	0

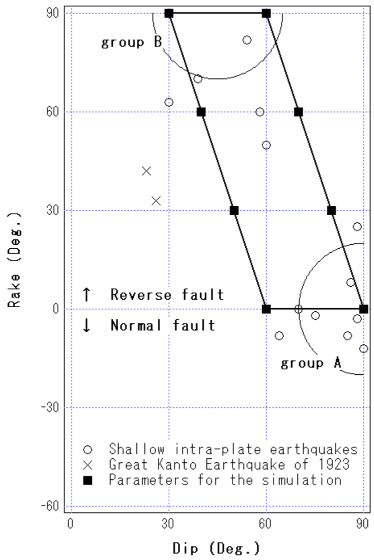

Fig.2 Mechanisms of past earthquakes and the parameters for the simulation.

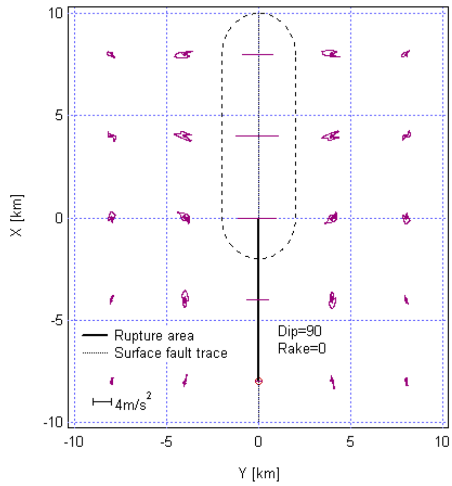

Fig.3 Acceleration trajectories for the mechanism of (dip=90°, rake=0°).

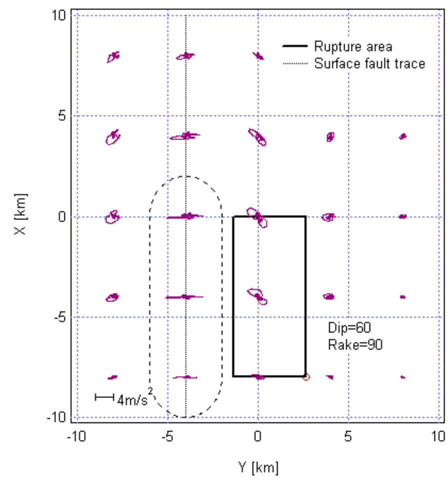

Fig.4 Acceleration trajectories for the mechanism of (dip=60°, rake=90°).

mechanisms of these earthquakes. Also plotted in **Fig.2** are the mechanisms identified for the subevents of the 1923 Kanto Earthquake[9], which is not an intra-plate earthquake. It is observed that the mechanism of this earthquake is quite different from those of intra-plate earthquakes probably due to the coupling of two tectonic plates. It should be noted that the ensuing simulation is not intended to cover inter-plate earthquakes.

In the simulation, an asperity with an area of 8×8km^2 is assumed. The center of the asperity is assumed to be 8km deep. The rupture initiates at one corner at depth and propagates radially with a velocity of 2.8km/s. The final dislocation is assumed to be uniform within the asperity and is 1.92m. The moment magnitude of the asperity is 6.3. The rise time is 1.2 seconds. A boxcar-type slip velocity time function is assumed. It should be noted that, in this simulation, ground motions from only one asperity is evaluated. Since our focus is on the predominant direction of ground motions, it is easy to deduce the results with multiple asperities from those with only one asperity.

Ground motion accelerations with frequencies lower than 2Hz are computed for 25 sites in the near-source region.

(3) Results

Fig.3 indicates the results for a pure strike-slip case (dip=90°, rake=0°). In **Fig.3**, the thick line indicates the surface projection of the asperity. The open circle indicates the surface projection of the rupture starting point. The dotted straight line indicates the surface fault trace defined as the intersection of the fault plane and the ground surface. The acceleration trajectories are indicated at 25 sites in the near-source region. As can be seen in **Fig.3**, the region in the direction of rupture propagation (surrounded by dotted line) is exposed to a large amplitude ground acceleration which is polarized perpendicular to the strike of the fault. This is exactly what the intuitive explanation in the introduction tells. **Fig.4** indicates the results for a pure dip-slip case (dip=60°, rake=90°). In **Fig.4**, the thick rectangle indicates the surface projection of the asperity. The meanings of the open circle and the dotted straight line are the same as those in **Fig.3**. The acceleration

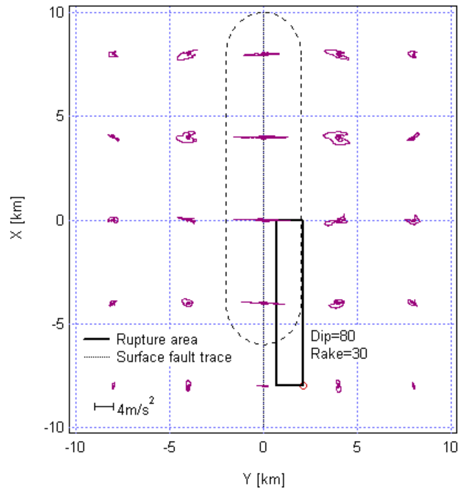

Fig.5 Acceleration trajectories for the mechanism of (dip=80 °, rake=30 °).

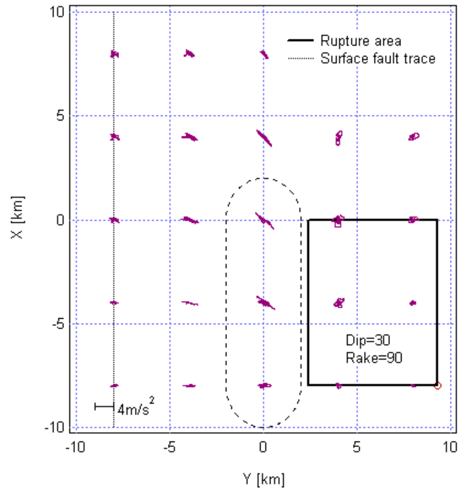

Fig.7 Acceleration trajectories for the mechanism of (dip=30 °, rake=90 °).

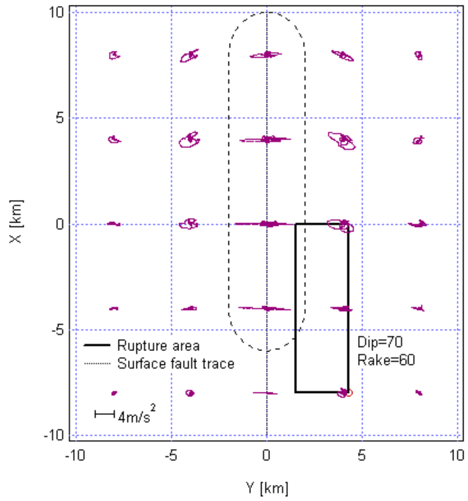

Fig.6 Acceleration trajectories for the mechanism of (dip=70 °, rake=60 °).

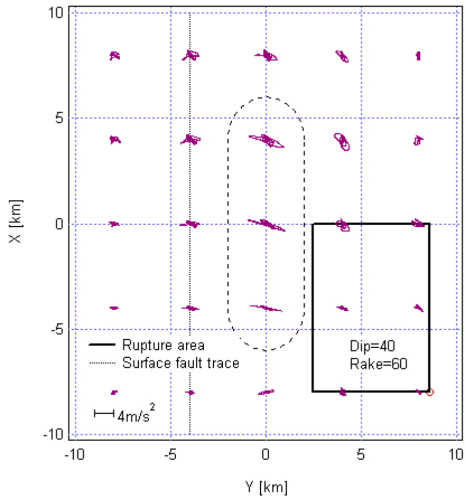

Fig.8 Acceleration trajectories for the mechanism of (dip=40 °, rake=60 °).

trajectories are indicated at 25 sites in the near-source region. As shown in **Fig.4**, the region in the vicinity of the updip projection of the asperity (surrounded by dotted line) is exposed to a large amplitude ground acceleration that is polarized perpendicular to the strike of the fault. This is exactly what the intuitive explanation in the introduction tells. The results for other source mechanisms are shown in **Figs.5-10**. In these figures, the meanings of rectangles, open circles and the dotted straight lines are the same as those in **Fig.4**. The results indicate a very robust tendency for a strike-normal component to be predominant in the area of most intensive excitations (surrounded by dotted line) irrespective of the source mechanism. Although the strike-parallel component is predominant at some sites, the amplitude of the excitation is relatively small at these sites.

3. FEM ANALYSES

A gravity-type quay wall with a typical water depth of -7.5m was chosen to be modeled for non-linear FEM analyses to show the effects of quay wall orientation on its residual deformation. A computer program called FLIP[10] is used for the analyses. The program can calculate the response of two-dimensional soil-structure system based on multiple shear mechanism. The model involves the caisson (9.9m high and 12.4m wide), the soil beneath and behind the caisson and the sea water. The soil parameters (**Table 3**) are the same as those used for the simulation of the damage at Kobe Port[11] except that the excess pore water pressure is omitted in the present model. The gravel and the sandy soil beneath the caisson is 2.1m and 9.4m thick, respectively.

The model quay wall is subject to the simulated ground accelerations. The quay wall is assumed to be oriented either parallel or perpendicular to the strike

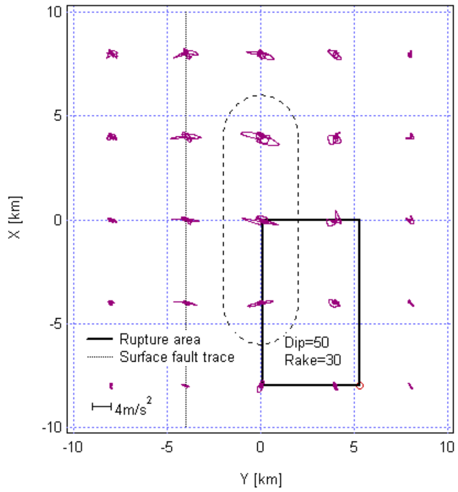

Fig.9 Acceleration trajectories for the mechanism of (dip=50 ° , rake=30 °).

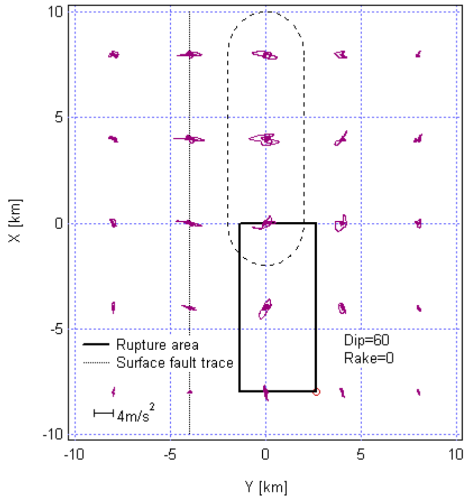

Fig.10 Acceleration trajectories for the mechanism of (dip=60 ° , rake=0 °).

of the fault. If the quay wall is oriented parallel to the strike of the fault, it is subject to the strike-normal ground acceleration and vise versa. Since two components of ground accelerations have been simulated at each of the 25 sites for each of the 8 source mechanisms, the total number of the cases of the non-linear FEM analyses is 400. Typical examples of simulated accelerations are shown in **Fig.11**.

The results are shown in **Fig.12**. Each plot corresponds to one of the 200 combinations of the source mechanisms and the sites. The abscissa indicates the deformation of a strike-parallel quay wall. The ordinate indicates that of a strike-normal quay wall. The arrows indicate data for which the ordinate is zero. The results clearly indicate that the deformation of a quay wall is significantly smaller if it is oriented perpendicular to the strike of the fault.

In the foregoing non-linear FEM analyses, the excess pore water pressure is omitted. This means

Table 3 Soil parameters for the non-linear FEM analyses.

Material	Density (t/m^3)	Initial shear modulus (kPa)	Effective comfining pressure (kPa)	Friction angle (deg)
Gravel	2.0	180000	98	40
Sandy soil	1.8	58320	106	37
Cohesive soil	1.7	74970	143	30

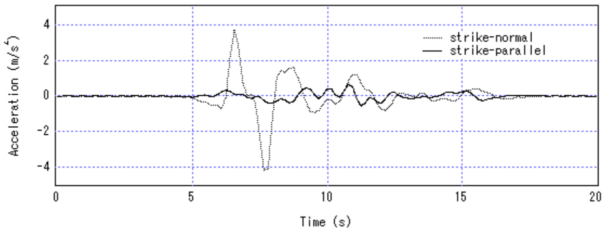

Fig.11 Typical examples of strike-normal (broken line) and strike-parallel (solid line) simulated accelerations (dip=60 ° , rake=90 ° ,X=0km,Y= - 4km).

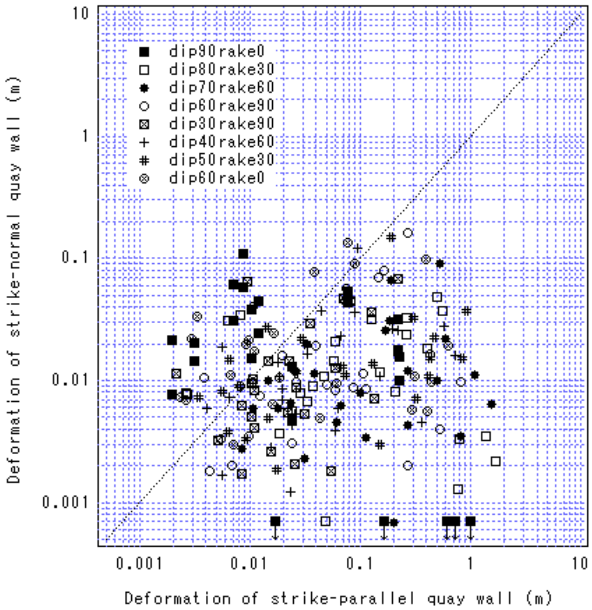

Fig.12 Residual deformations of quay walls oriented parallel or normal to the fault strike.

that the model corresponds to a quay wall for which adequate liquefaction mitigation have been implemented.

The author's opinion is that the earthquake disaster mitigation utilizing the fault orientation should always be accompanied with some adequate liquefaction mitigation. In case of liquefaction, it is anticipated that the orientation dependence of the damage will be reduced, although the damage at Kobe Port was still strongly orientation dependent in spite of the apparent liquefaction[12].

4. CONCLUSION

Two kinds of analysis have been conducted, namely, simulations of near-source ground motions for various source mechanisms and non-linear FEM analyses of a quay wall subject to the simulated ground motions. The results clearly indicate that the deformation of a model quay wall is quite dependent upon its orientation with respect to the strike of the fault. Based on the above results, and paying attention to the fact that there is much uncertainty in predicting the dip angle, the rake angle and the rupture starting point of a future earthquake, it is recommended that important quay walls that are constructed in the vicinity of an active fault should be oriented perpendicular to the strike of the fault.

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