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DEVELOPMENT OF PROTOTYPE OF INTEGRATED EARTHQUAKE DISASTER SIMULATOR USING DIGITAL CITY AND STRONG GROUND MOTION SIMULATOR WITH HIGH-RESOLUTION

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SUMMARY

An analysis method called macro-micro analysis method has been proposed to compute strong ground motion distribution with highest spatial and temporal resolution, which is based on multi-scale analysis. Strong ground motion (SGM) simulator with high-resolution is developed using this analysis method. Basic validity is verified by comparison with measured data. Prototype of Integrated Earthquake Disaster Simulator (IEDS) is also developed using this SGM simulator and digital city for realistic earthquake disaster simulation of possible earthquake. Computed SGM distribution is used to shake a computer model of a virtual town, which consists of various structure models. The model is constructed by using data, which are stored in Geographical Information System and CAD. Dynamic responses are computed for all structures subjected to the SGM at each site. All resulting dynamic responses are stored in computer system and earthquake disaster of this virtual town is estimated by various indexes.

INTRODUCTION

Realistic earthquake disaster simulation of possible earthquake is important for making rational counter plan. This paper proposes such a simulation method, Integrated Earthquake Disaster Simulator (IEDS) using strong ground motion (SGM) simulator with high resolution and digital city.

Though full 3-D numerical simulation can provide SGM information with high resolution, there could be two major difficulties: 1) huge amount of computation; 2) uncertainty of soil-crust information. For resolving these difficulties, new analysis method, macro-micro analysis method is proposed. This analysis method takes advantage of the multi-scale analysis and the bounding media theory. The multi-scale analysis can reduce computation amount required at one time, and the bounding media theory can resolve the uncertainty of soil-crust structure information.

For more reduction of computation amount, the finite element method with voxel element is applied for wave propagation simulation. The borehole data is used for modeling soil-crust structure. Geographical Information System with auto-modeling tool for soil-crust structure is developed to handle a huge amount

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of borehole data efficiently. In order to verify the basic validity and effectiveness of this method, reproduction of earthquake observed in Yokohama City is attempted.

Digital city is constructed using available digital data: CAD data for buildings, concrete structure, steel structure and so on. Using SGM simulator with high resolution, digital city and simulation programs for each structure, earthquake disaster simulation is made. And the resulting earthquake disaster is visualized and estimated by various indexes. These development and discussion present the basic usefulness of IEDS.

In this paper, overview of SGM simulator with high-resolution is explained. After verification of this SGM simulator, as an illustrative example of this SGM simulator, prototype of IEDS is developed. Estimation of earthquake disaster in this virtual town by some indexes present potential usefulness of IEDS.

DEVELOPMENT OF STRONG MOTION SIMULATOR WITH HIGH-RESOLUTION

A prototype of SGM simulator with high resolution has been developed [(1)]. This simulator is based on the macro-micro analysis method that takes advantage of the multi-scale analysis [(2)] for efficient and accurate numerical computation and the bounding medium theory [(3)]. Wave propagation processes from fault to ground surface can be computed with sufficiently high spatial and temporal resolution.

SGM simulator computes fault mechanism, wave propagation through the heterogeneous crust and amplification near ground surface. The key issue of SGM simulator is the three dimensional topographical effects in large and small length scales.

The multi-scale analysis of the macro-micro analysis method, which is based on singular perturbation expansion, uses spatial coordinates of two length scales. The macro-analysis and the micro-analysis are set for computing the wave propagation in the geological scale with low resolution and in each town or ward in engineering scale with high resolution, respectively.

The uncertainty of geological and ground structures is resolved by considering a stochastic model, which prescribe stochastic distribution of structure configuration and mechanical properties, such as the mean and the variance. The bounding medium theory is used to make fictitious but deterministic models for the stochastic model such that the mean responses of the stochastic model can be bounded by the responses of these deterministic models.

Macro-micro analysis is constructed based on combination of the bounding medium theory and the singular perturbation. We summarize the procedures of macro-micro analysis method as follows:

a) Construct a stochastic model for crust and ground structures of a metropolis, by prescribing the mean and variance for the configuration (such as the location of the interface between neighboring layers) and the material properties (such as the elasticity and the density) for each layer.
b) Applying the bounding media theory, determine two fictitious but deterministic models that provide optimistic and pessimistic estimates of the mean behavior of the stochastic model.
c) Applying the singular perturbation expansion, make multi-scale analysis to calculate a distribution of strong motion in the target metropolis; the multi-scale analysis consists of the macro-analysis with low spatial resolution and the micro-analysis with high spatial resolution, i.e., in macro-analysis, compute the first-order term for whole ground structure under the metropolis at the spatial resolution of 100[m]. In micro-analysis, compute the second-order term for each small region of ground structure under the metropolis at the spatial resolution of 1[m].

Figure 1 presents a schematic view of the above procedures of the macro-micro analysis method.

The prototype of SGM simulator is able to compute the strong motion distribution with high spatial and temporal resolution, say, 1 or 2 meter and 10 Hz. Such resolution is needed for the dynamic analysis of structures whose natural frequency goes up to a few Hz. Also, in this resolution, the wave amplification near the ground surfaces that consist of soft layers is computed accurately, and some three dimensional topographical effects on the amplification can be computed. In next section, three actual earthquakes are reproduced in Yokohama city. Comparing the maximum velocity of simulated results with observed data at 17 seismograph sites, the validity of SGM simulator is checked.

NUMRICAL EXAMPLE

Earthquake reproduction in Yokohama City

We carry out a numerical simulation in Yokohama city to reproduce three actual earthquakes. The characteristics of the three earthquakes are shown in Table 1. Figure 2 shows the location of epicenters of the three earthquakes. The results of simulation are compared with data, which are observed at 17 sites of seismographs located in Yokohama city.

We select a domain of 40 X 30 X 70 km (in the EW, NS and UD directions) that covers the whole Yokohama city and the epicenters of the three earthquakes. Geological structure of this domain is modeled for the macro-analysis; see Figure 3. The spatial resolution of this model is 1 km. There are 4 layers in the model; see Table in Figure 3 for the properties of the layers (a, b and r indicate P wave velocity, S wave velocity and density respectively). The resolution of macro-analysis near ground surface is 40 X 40 X 40 m. The result of macro-analysis is guaranteed till 1.0Hz. The higher frequency components, say, the frequency from 1.0Hz to 5.0Hz is extrapolated by using a statistical spectral form, which is estimated by taking the average of the observed spectral at bedrock for every earthquake.

For micro-analysis, three dimensional ground structures are constructed around the 17 seismographs separately using borehole data. The domain 240 X 240 X 60 m is with the resolution of 2 X 2 m on the surface. The result of micro-analysis is guaranteed till 5.0Hz. Fixing the configuration of the interfaces between the soil layers, a normal distribution for uncertainty material properties (i.e., the P wave velocity, the S wave velocity and the density) is assumed; the mean value is estimated according to the soil styles and the coefficient of variance is set as 1.0. Applying boundary medium theory, the optimistic and pessimistic cases are computed.

As an index, the maximum velocity of optimistic and pessimistic cases is compared with the measured data; see Figure 4. Although for some cases computed and measured are in good agreement; for most cases, the agreement is not satisfied. This is due to the shortcomings in macro-micro analysis:

a) A point source model with a ramp function is used as the source of earthquake. The simple source model cannot produce strong motion of high frequency.
b) The statistical spectral form of high frequency is estimated as the average of the sites located within the same region. The local effects are considered in micro-analysis, say, from bedrock to ground surface; but for the wave propagation from fault to bedrock, local effects of higher frequency components are not well considered.
c) The surface of the model for geological structures in macro-analysis is assumed as flat, but actually the maximum elevation difference is more than 400 meter. The surface shape has large effect on the distribution of the SGM.
d) The material properties of soil layers in micro-analysis are estimated as the function of soil style. But actually material properties are much more complicated. For the same soil style, the material properties are in big difference for different locations.

Prototype of Integrated Earthquake Disaster Simulator
Application example of IEDS is shown for presentation of potential usefulness. Virtual town is constructed on computer, which consist of various structures i.e. bridges, houses, interchange of highway and so on; see Figure 5. Each structure data has identical ID and all digital data is utilized by IEDS platform system like Geographical Information System. In IEDS, this digital city is shaken by SGM simulator with high resolution and dynamic response is computed by simulation tool specialized for each structure. These simulation tools are a plug-in for IEDS platform system.

As an illustrative example, simple simulation is made using this digital city. Plane wave of Ricker's wavelet is input for bottom surface of this digital city. SGM is computed by SGM simulator with high resolution. Using resulting SGM information, each dynamic response of these structures is computed and resulting dynamic response is stored into IEDS platform system. For simplicity, linear elastic simulation tool is applied as these plug-in in current IEDS. Since all data is stored in this system, we can easily visualize and estimate response of this digital city. Figure 6 shows maximum displacement norm distribution. Each dynamic response of structure is different with each other, since SGM distribution is so complicated and nature of each structure is different with each other. As a result whole dynamic response of digital city is so complicated.

Since each structure has identical ID, we can easily pick up dynamic response of specific structure. Dynamic response of bridge 1 is picked up and estimated by maximum acceleration; see Figure 7. Figure 8 shows comparison of dynamic response on specific points; see Figure 7 for point number. Although bridge 1 is not so large structure, Figure 7 and 8 indicates dynamic response could be drastically changed depending on complexity and location of structure.

CONCLUDING REMARKS

A macro-micro analysis method for prediction of SGM with highest spatial and temporal resolution is explained. SGM simulator with high-resolution is developed using this analysis method. Basic validity is verified by comparison with measured data. Prototype of IEDS is also developed using this SGM simulator and digital city for realistic earthquake disaster simulation. A simple earthquake simulation in a virtual town is made by IEDS. Such simulation becomes more realistic and reliable as the earthquake simulation is made with higher accuracy and resolution. Although the limitation of constructing a computer model should not be underestimated, the earthquake simulation will be useful for the earthquake hazard and disaster prediction.

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Table 1: Properties of three target earthquakes.

Case	Occur time	Magnitude	Epicenter	Strike (^{o})	Dip (^{o})	Rake (^{o})	Depth (km)
1	1999/08/11	4.0Mj	35.4000N 139.8302E	62	85	73	53
2	2000/09/29	4.5Mj	35.5222N 139.7350E	318	80	-120	74
3	2000/10/11	4.1Mj	35.5315N 139.7232E	133	90	114	86

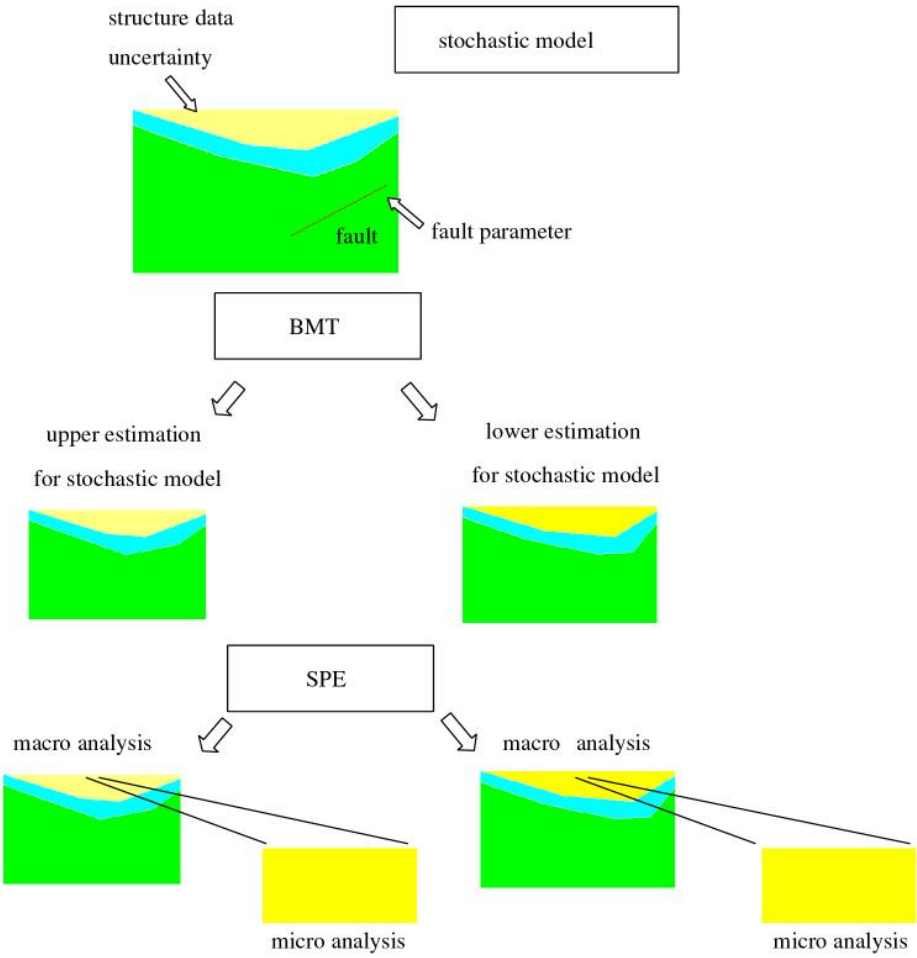


Figure 1: Flowchart of macro-micro analysis method

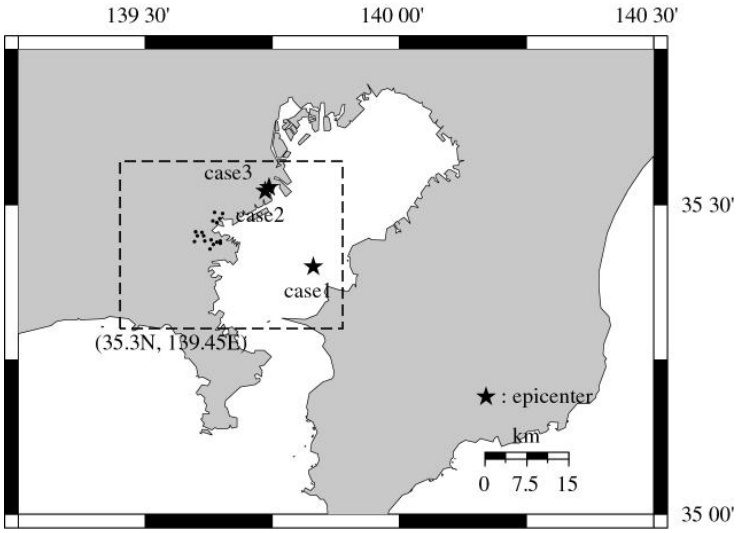
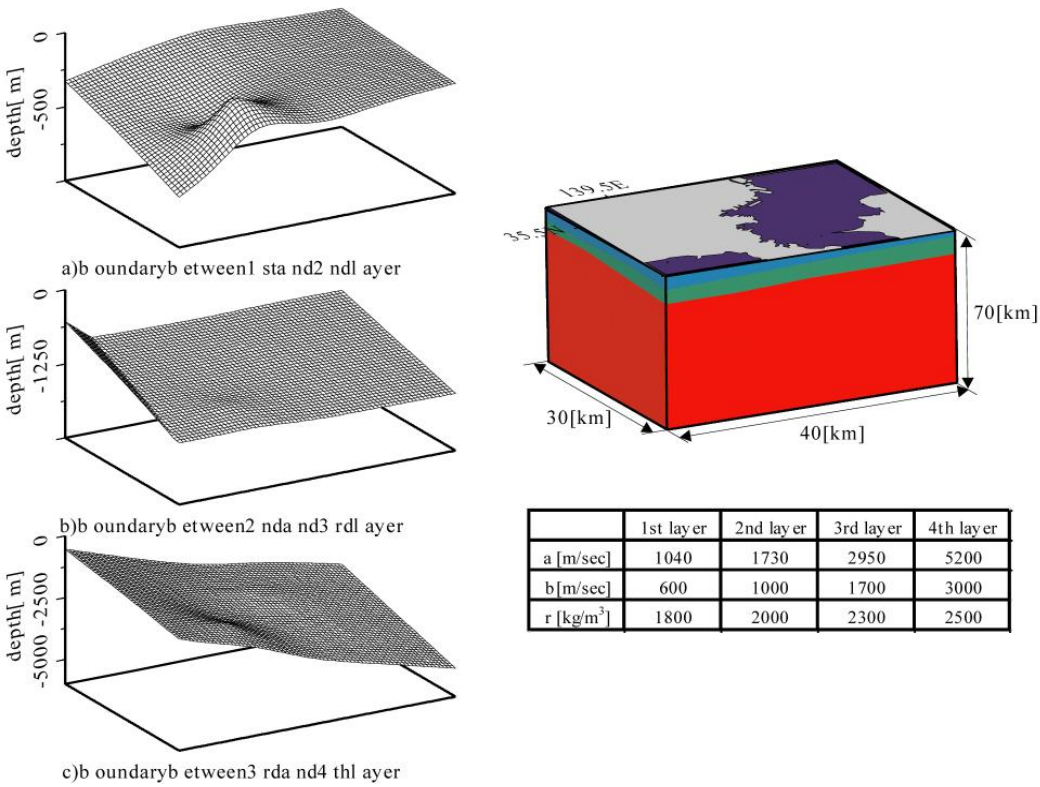
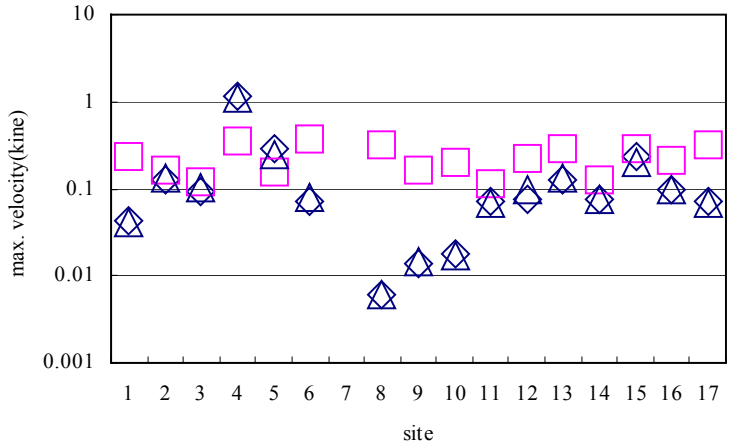


Figure 2: Target area and earthquakes

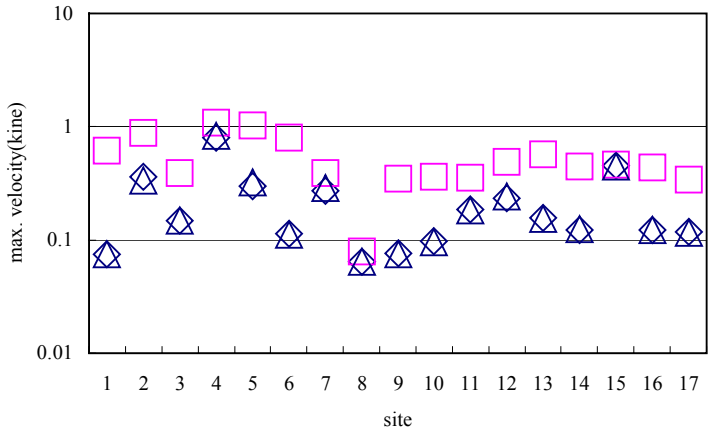


	1st layer	2nd layer	3rd layer	4th layer
a [m/sec]	1040	1730	2950	5200
b [m/sec]	600	1000	1700	3000
r [kg/m^3]	1800	2000	2300	2500

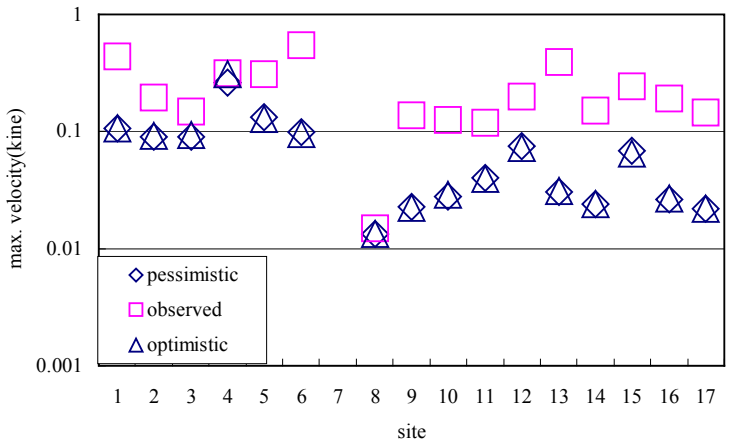
Figure 3: Model for macro analysis method



c) case 1



b) case 2



c) case 3

Figure 4: Comparison with measured data in E/W direction

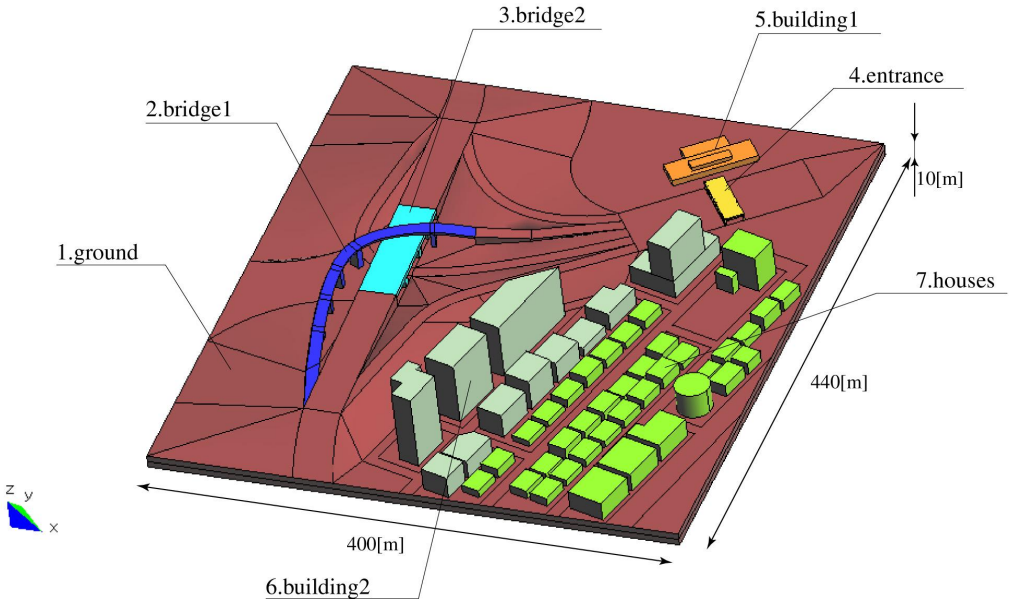


Figure 5: Digital city constructed on IEDS platform system

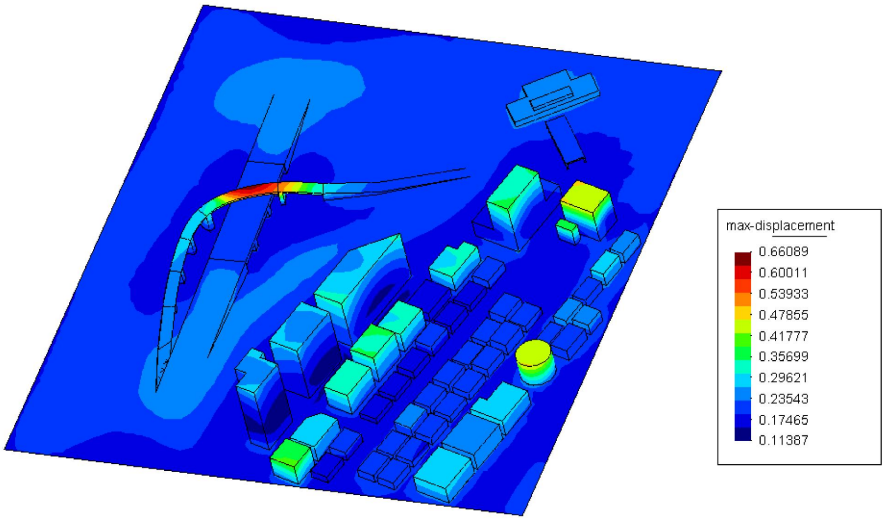


Figure 6: Maximum displacement norm distribution in digital city

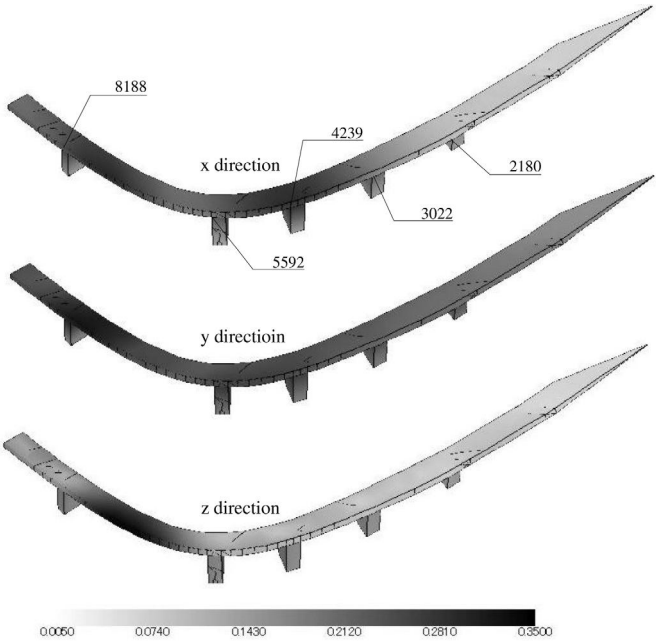


Figure 7: Maximum acceleration distribution on bridge 1.

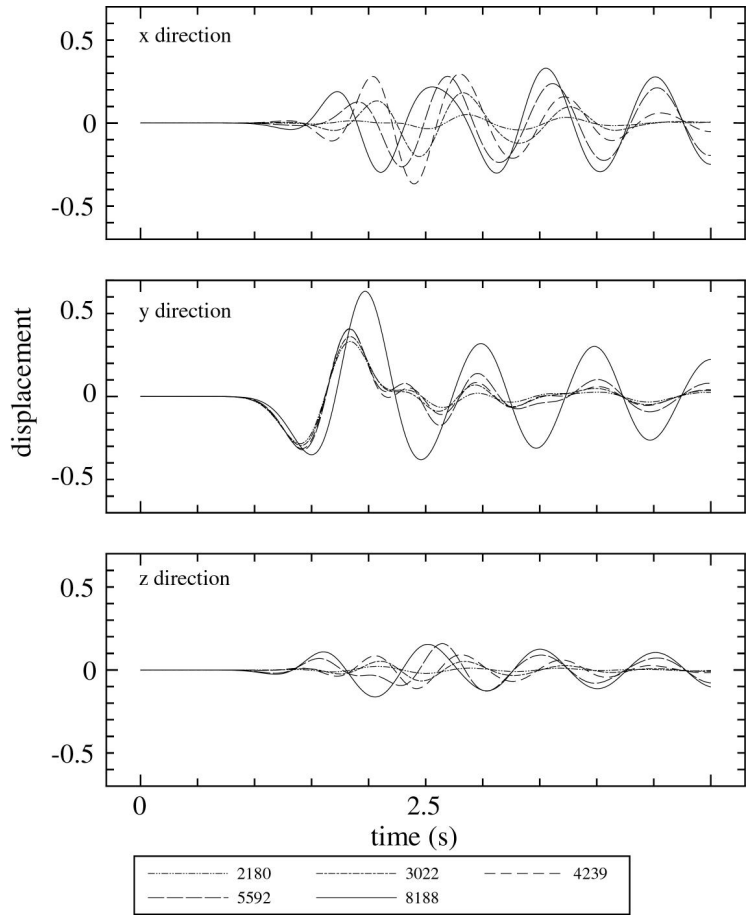


Figure 8: Dynamic response at specific points on bridge 1.