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EFFECT OF SOIL STIFFNESS AND GROUND DISPLACEMENT IN EARTHQUAKE RESPONSE OF BRIDGES WITH PILE FOUNDATION

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ABSTRACT: Dynamic analysis was carried for earthquake response of prototype bridge structures with pile foundation in clay soil with sand base. Analysis was carried out for different soil stiffness parameter, *Vs*(shear wave velocity)-value using "Single input model" which does not consider the ground displacement and "Penzien model" which considers ground displacement. It was found that with increasing soil stiffness, effect of ground displacement on response becomes smaller and the two models yielded similar results. Consideration of ground displacement has great effect in earthquake response for clay with shear velocity, *Vs* less than 100 m/sec i.e. for soft clay. *Vs*-value of 150 m/sec may be considered the critical velocity after which consideration of ground displacement has much less effect and thus simpler "Single input model" may be used. This corresponds to cohesion, c_u value of 60 kPa and N-value of 4 approximately. It was also shown that strain dependence of shear modulus and damping have significant effect on displacement of the soil deposit.

INTRODUCTION

In the region where structures are constructed on pile foundation penetrating through soft clay layer and resting on base of sand layer, clay layer characteristics play a significant role in the structural response to earthquake loading. In this situation, effect of ground displacement must be considered depending on the shear wave velocity level of the soft clay layer. This situation is reflected in "Railway Bridge Standard" revised in October, 1999 where it recommends to use "Penzien model" for soft clay thus considering the ground displacement and pile soil interaction.

Large changes in the earthquake resistant design codes such as "*The Code for Road Bridge 5 Earthquake-Resistant Design Edition and Explanation (in Japanese)* (the Road Bridge Code)" and "*Design Standard and Explanation of Railway Structure*" were made after experiencing the devastating "1995 Kobe Earthquake" which hit a highly urbanized area of western Japan with magnitude of M=7.2 at very short distance. Serious damages were caused to the bridge structures. Type II ground motion which developed during earthquake with magnitude of about 7-7.2 at very short distance from urban area, in addition to the Type I ground motion which developed in the plate boundary-type earthquake with magnitudes of about 8 was included in the codes. Elasto-plastic analysis of ground, foundation and superstructure as one body must be carried out, since acceleration response spectrum of type Ⅰ, Ⅱ earthquake vibration shown in this revision is very big.

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In Saga region, the shear wave velocity of Ariake clay layer is about 40～100 m/s from 5.0 m to about 30.0 m thickness, and most of the structures are supported by pile foundations. At present, it has been planned to construct high standard motorway of overhead style in this soft ground zone and as such it is required to establish the basic guideline for the earthquake-resistant design of bridge structure with long pile foundation in soft ground.

In order to establish earthquake-resistant design guideline of the pile foundation-superstructure system in soft ground zone of N value almost zero, this study examines the safety by carrying out elasto-plastic dynamic analysis of the pile foundation - superstructure system considering the displacement of the ground. By varying the soil properties from soft clay to hard clay, effect of soil stiffness change to the bridge response are examined. Thus it is investigated at which level of clay stiffness, ground displacement influence to the response becomes less significant. Effect of strain dependence of clay rigidity ratio(*G/Go*) to the ground displacement is also examined. *Go* is the shear modulus at very small strain range and *G* is the variable shear modulus at any strain level.

Previously, there were lack of suitable computer codes to handle dynamic displacement input and different non-linear models and this might be one of reasons for not considering rigorous dynamic earthquake analysis in the past. Instead simple "Seismic Co-efficient method" and "Static non-linear spectrum method" only were used. For the purpose of the present study, object orientated elasto-plastic structural analysis system "SESAS" have been developed in Saga University Structure System Laboratory. This program can handle static and elasto-plastic analysis, eigen-value analysis, dynamic elasto-plastic analysis. It incorporates many material nonlinear models such as bi-linear, tri-linear, tri-linear Takeda etc. This program is very suitable to carry out dynamic analysis which the Railway Bridge Standard recommends and also for general purpose dynamic analysis.

ANALYTICAL MODELS

For "Penzien model" type analysis as recommended by Railway Bridge Standard for soft clay region, two analytical models are necessary. One is soil deposit model and the other is bridge structure integrated model. The two models are described below. In "Single input model", the former soil deposit model is not necessary since displacement of the soil deposit is not considered in this model.

Soil Deposit Model

In this model, for using k-SHAKE(soil deposit non-linear analysis software), soil deposit is divided into many layers based on the variation of soil properties and depths for displacements to be used in bridge structure integrated model. Soil properties such as shear wave velocity, strain dependence of rigidity ratio(*G/Go*) and damping(h%) etc. are input for every layer. Soil properties are shown in Table 1. To carry out the analysis for the effect of soil stiffness change, uniform soil deposit up to about 16.0 m resting on sand base which is a typical characteristic of saga clay was considered and shear wave velocity was increased from 80→180 m/sec (80, 90, 100, 120, 150 & 180 m/sec). Shear wave velocity was chosen as a measure of increasing soil stiffness, since the soil deposit displacement is greatly dependent on it. Based on the soil properties of Saga clay, two *G/Go* curves, Rokkaku2(for *Vs* <100 m/sec) and Rokkaku3(for *Vs* 100→180 m/sec) were selected and are as shown in Fig. 1. Cohesion value was calculated from the following equation rearranged from equation in book by Shima Hiroyasu (1996):

$$c_u = \left(\frac{Vs}{27.28} \right)^{2.3981} \tag{1}$$

where c_u is the cohesion value in kPa and Vs is the shear wave velocity in m/sec.

Correlation of Vs and N-value may also be done following Road Bridge Code equation:

$$Vs = 100 N^{\frac{1}{3}} \tag{2}$$

where Vs is the shear wave velocity in m/sec and N is the SPT no.

Table 1 Soil Properties

Soil Layers	Layer thickness (m)	Shear wave velocity, Vs (m/sec)	Cohesion, c_u (kPa)	Angle of friction, ϕ^o
Clay	15.7	Varies 30-250	Varies(Eq. 1) 1.26-202.86	0
Sand-base layer	1.4	400	0	40

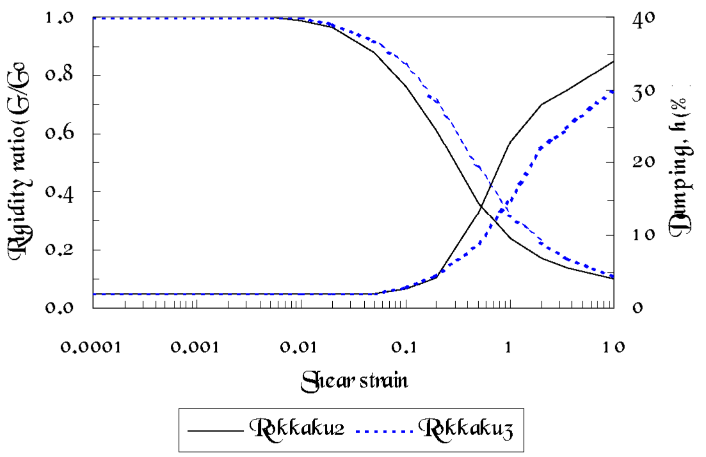

Fig. 1 Strain dependence of rigidity ratio and damping of clay

Other necessary parameters for the analysis, such as vertical spring constant at the pile tip, lateral coefficient of sub-grade reaction, upper limit of sub-grade reaction, lateral yield displacement, equivalent damping of each structural elemet, etc. were obtained based on the rule of the Road Bridge Code. The Ramberg-Osgood model which considers elasto-plastic behaviour of soil was used as a hysteresis model of the ground in the k-SHAKE analysis.

Bridge Structure Integrated Model

A typical prototype bridge structure based on Saga soft clay region was chosen for the analysis. Detail dimensions of single pier bridge -pile foundation are shown in Fig. 2.

Corresponding analytical model is prepared and is as shown in Fig. 3 to be used in SESAS (general non-linear structural analysis software developed in Structural System Laboratory, Saga University). Lumped mass model was used for piles and the pier. Concentrated mass at the top accounts for the total weight of bridge deck, girders etc. The concentrated elasto-plastic bilinear soil spring at each nodal position was adopted in the elasto-plastic dynamic analysis program instead of distributed soil springs. By the static elasto-plastic analysis it has been shown that the result obtained from distributed spring model and concentrated spring model is almost identical if sufficiently small element length is adopted. Following Road Bridge Code, plastic hinge was introduced at the bottom level of bridge pier. The necessary *M*-*θ* model (tri-linear) was prepared from *M*-*ϕ* model. Calculation was carried out based on Road Bridge Code. Tri-linear Takeda model was used in the analysis for this plastic hinge.

THE ANALYSIS PROCEDURE

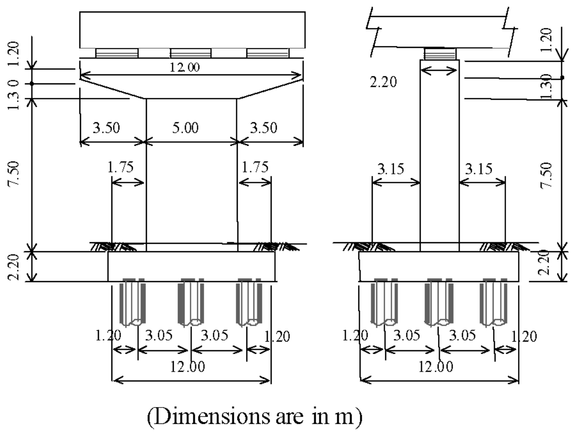

Fig. 2 Bridge structure for analysis

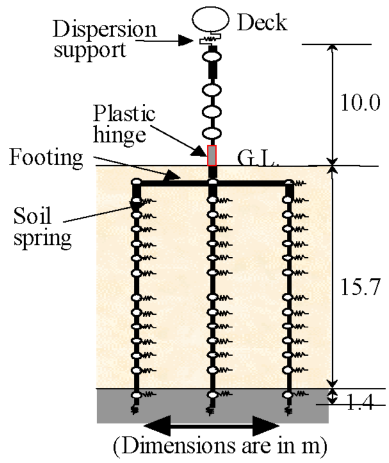

Fig. 3 Finite element model of the bridge

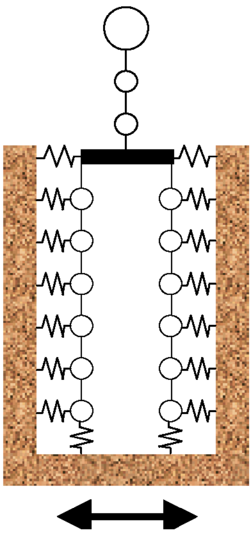

Fig. 4 Single input model

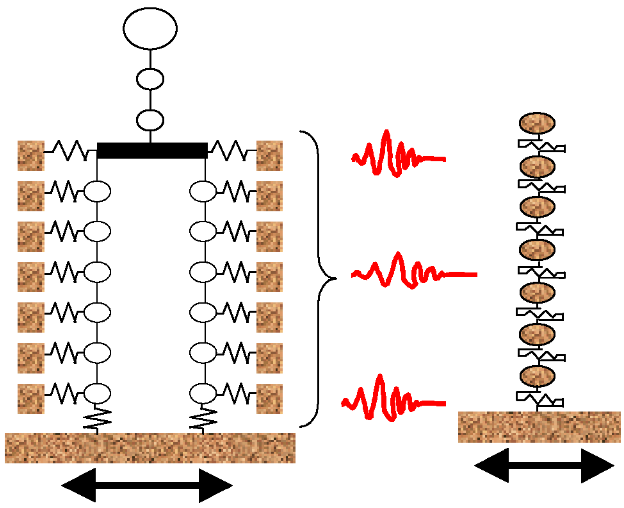

Fig. 5 Multi-point input model (Penzien model)

For varying soil properties as mentioned above, the analysis was carried out by 2 models that were mentioned in the Railway Bridge Standard. The first one is the model shown in Fig. 4 called the "single input model" where it is assumed that the ground supports the pile, not displaced. And, the ground acceleration by the Road Bridge Code was input at the bottom of the pile.

In this model the far end of soil springs are considered fixed. The second one is the model shown in Fig. 5 called multi-point input model (Penzien model). In this model, displacement of soil deposit is given as input in the far end of soil springs and the elasto-plastic analysis of the whole foundation -superstructure system is carried out. Before proceeding with Penzien model analysis, soil deposit displacement is obtained through nonlinear analysis by k-SHAKE. The analysis procedure is summarized in the flowchart (Fig. 6) below.

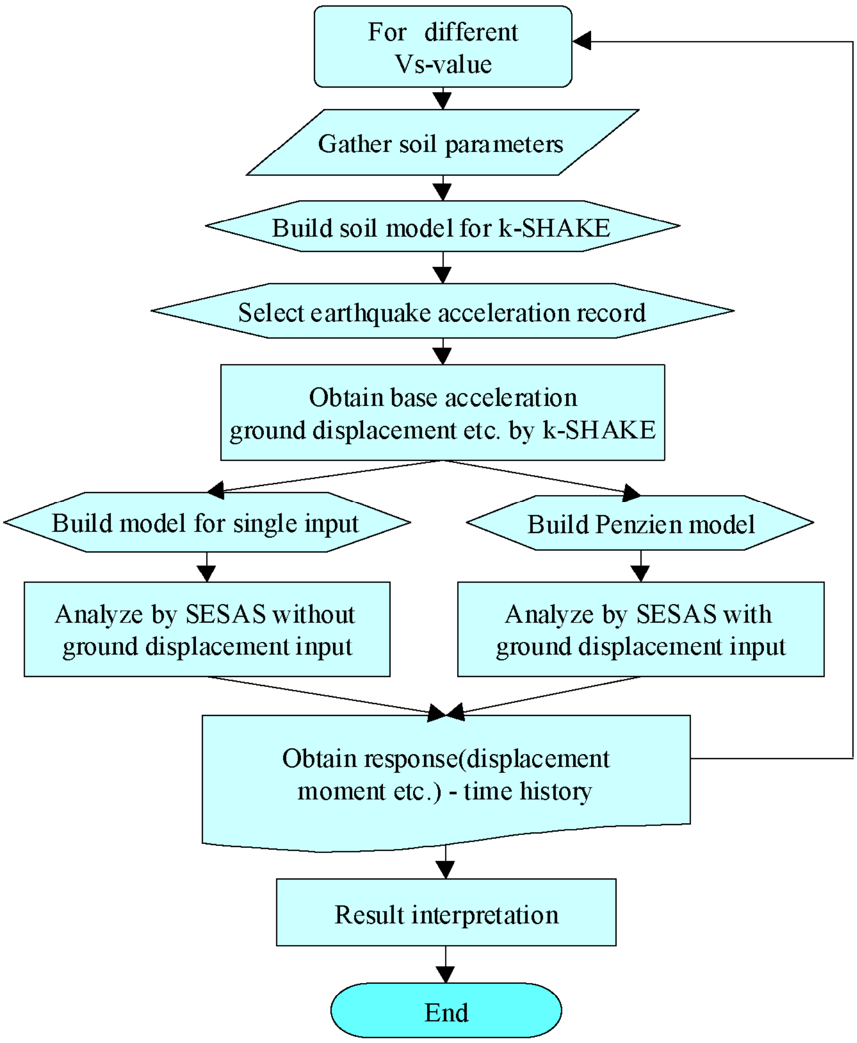

Fig. 6 Flow chart showing analysis step

In the first phase of the k-SHAKE analysis, acceleration time history in the base rock surface for given acceleration at the ground level, is obtained and then by non-linear analysis the displacement time history at each required depth corresponding to the base acceleration is obtained. Next, in the Penzien model, the base acceleration and soil displacement are given as input. To check the effect of strain dependence of rigidity ratio(*G/Go*), soil deposit displacement analysis was carried out for different shear wave velocity using both of Rokkaku2 and Rokkaku3 curves by k-SHAKE. Also, additional analysis using single input model only was carried out for *Vs* of 30, 60 and 250 m/sec to check the effect of soil stiffness change in this model in broader range. For this study, type I earthquake record was used for analysis.

As type Ⅰ vibration, the acceleration record (KUSHIROGAWA 1994 – Fig. 7) obtained in the type Ⅲ ground (soft ground), was selected. The accelerogram (Max 439gal) was corrected in order to suit the type Ⅰ seismic response spectrum. Saga region has been designated as the C region in the Road Bridge Code where the reduced acceleration of 0.7 times of the size of the spectrum is used. The acceleration record is shown in Fig. 7.

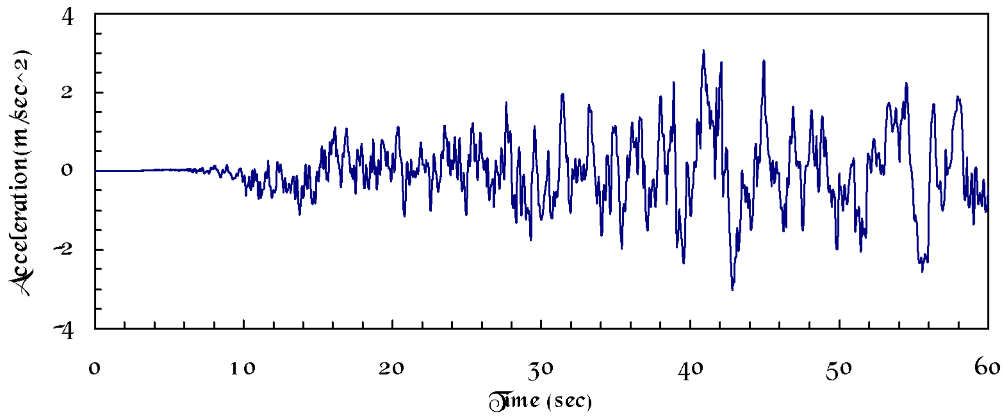

Fig. 7 Acceleration record of KUSHIROGAWA 1994 (Type I Earthquake)

RESULTS AND DISCUSSION

From the elasto-plastic analysis of the bridge models (two kind of models) as shown above, displacement-time history at every nodal points and internal forces at every element are obtained. Non-linear hysteresis behavior of the tri-linear rotational spring at the plastic hinge position of the bridge pier is shown in Fig. 9 and bi-linear hysteresis behavior of typical soil spring is also shown in Fig. 8. Maximum displacements at the top most point of the bridge pier (deck level) and maximum moment in the pile are quantities of interest for comparison purposes. These values are summarized in Table 2 for different shear wave velocity from both of Penzien model and Single input model. The quantities are plotted in Fig. 10 for maximum displacement and in Fig. 11 for maximum moment. It is noticed that in "Penzien model" analysis, very high displacement (0.845m) occurs for Vs = 80 m/sec and responses decrease rapidly with increasing shear wave velocity. In the severe earthquake as used in the present study(Fig. 7), high strain level occurs in the soil deposit where rigidity ratio (G/G_0) decreases sharply (Fig. 1). Again, for low shear wave velocity (soft clay) rigidity ratio (G/G_0) decreases more sharply (Rokkaku2 in Fig. 1) than that in the stiffer clay (Rokkaku3 in Fig. 1) which causes increase in soil deposit displacement (Fig. 16). In addition, shear modulus(G) decreases parabolically with Vs ($G = \rho Vs^2$). Shear strength also decreases sharply. These factors contribute to the high soil displacement by k-SHAKE analysis in the lower shear velocity region. Since Penzien model considers ground displacement its' responses are controlled mainly by soil deposit displacements and thus high values in the lower shear velocity region may be justified.

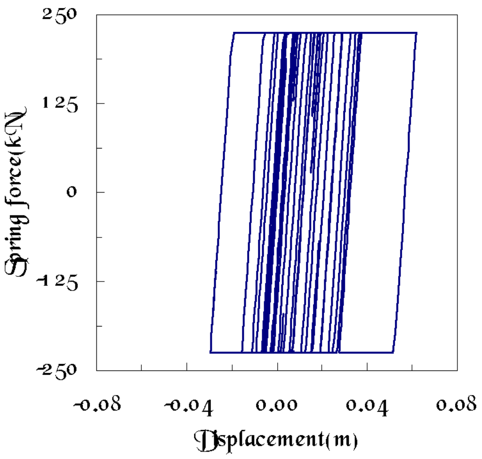

Fig. 8 Force-displacement curve at the soil spring

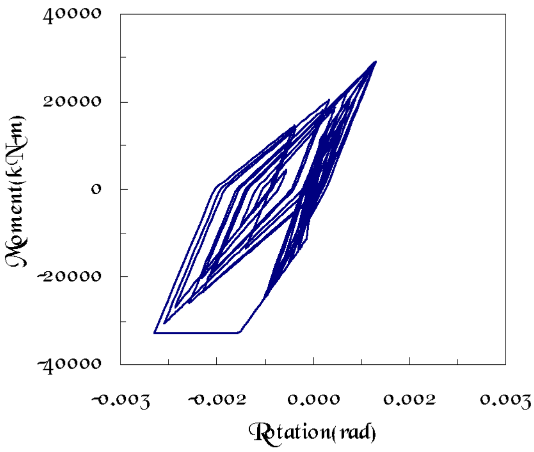

Fig. 9 Moment-rotation curve at the Plastic hinge

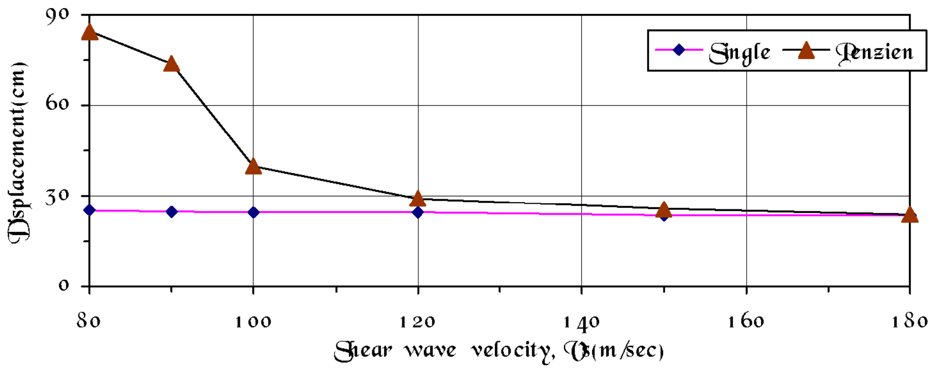

Fig. 10 Comparison of maximum displacement

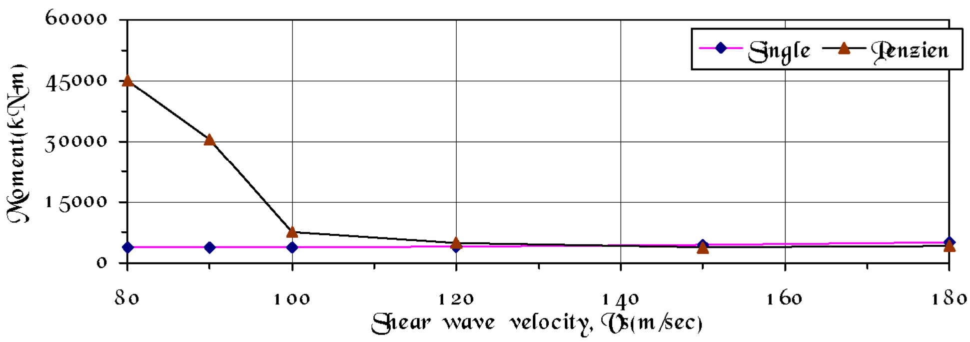

Fig. 11 Comparison of maximum moment in the pile

In the shear wave velocity range 80-180 m/sec, displacement in single input model decreases, while the maximum moment in the pile increases slowly. However, for *Vs*<60 m/sec, moment increases rapidly with the decrease of velocity in single model also. From the observation of the curves above, it is found that at about shear wave velocity 150 m/sec, the two models yielded similar results and this can be considered as the critical velocity after which the simpler single input model may be used for analysis without losing significant accuracy. For comparison purposes complete time-history of displacement and moment at pile top for *Vs*=90 m/sec and *Vs*=150 m/sec are shown in Figs. 12 - 15.

By Equation 1 and Equation 2, *Vs*=150 m/sec corresponds to cohesion value of 59.59 kPa say 60 kPa and N-value of 3.375 i.e 4 respectively. However, because of the approximate nature of the correlation equation shear wave velocity of 150 m/sec is recommended as the criteria. From this study, it can be said that shear wave velocity for a given site should be determined with great care by sufficient number of field tests since soil deposit displacement depends greatly on shear wave velocity.

Table 2 Maximum Displacement and Moment

Shear velocity, *Vs* (m/sec)	Maximum deck displacement (cm)		Maximum moment in the pile (kN-m)	
	Single input	Penzien	Single input	Penzien
30	30.09	-	5336	-
60	25.70	-	3605	-
80	25.16	84.51	3713	45057
90	24.60	73.83	3769	30546
100	24.41	39.86	3754	7600
120	24.46	29.09	3949	4950
150	23.46	25.63	4351	3714
180	23.58	23.80	5032	4185
250	24.14	-	7019	-

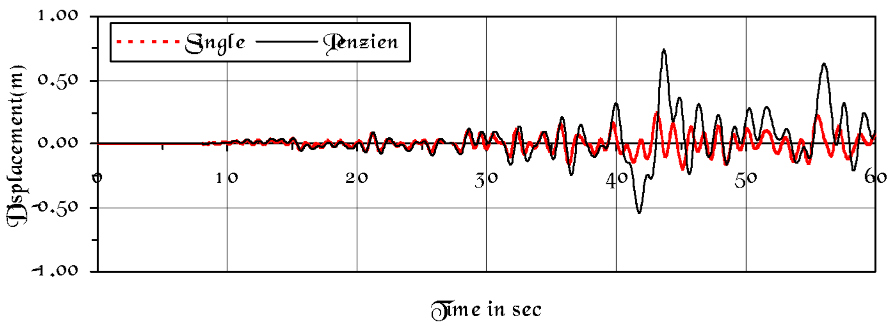

Fig. 12 Comparison of deck displacement time history for Vs = 90 m/sec

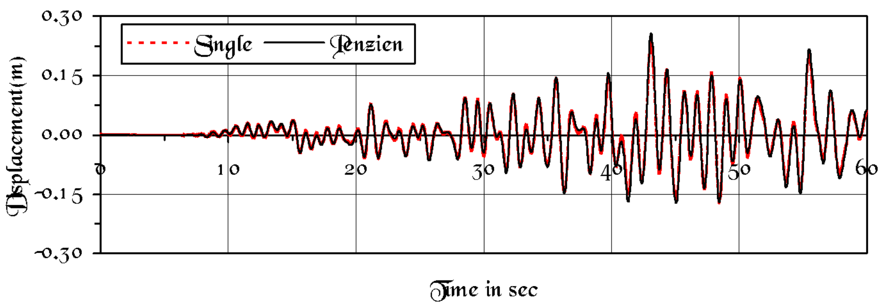

Fig. 13 Comparison of deck displacement time history for Vs = 150 m/sec

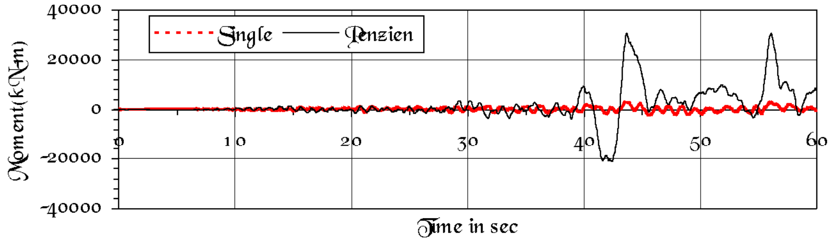

Fig. 14 Comparison of pile top end moment time history for Vs = 90 m/sec

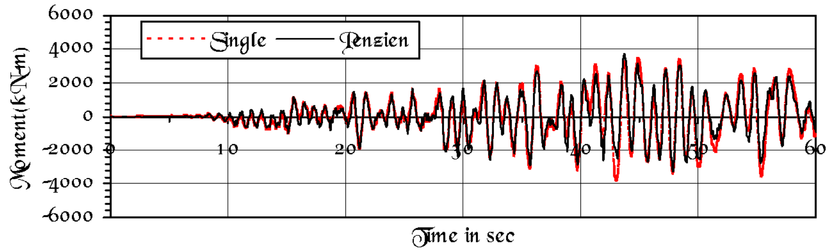

Fig. 15 Comparison of pile top end moment time history for Vs = 150 m/sec

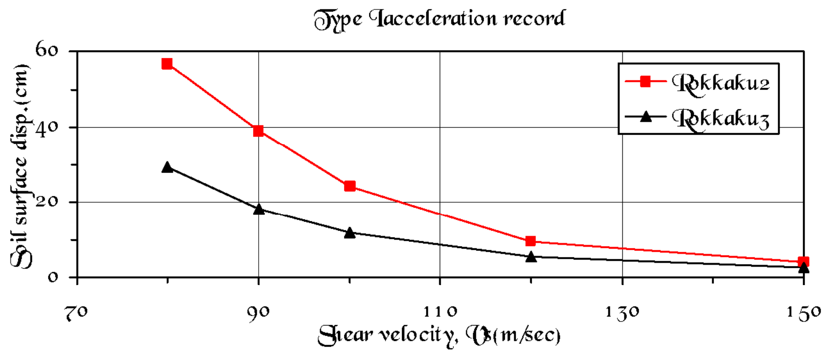

Fig. 16 Effect of strain dependence of rigidity ratio(G/Go) and damping, h (%)

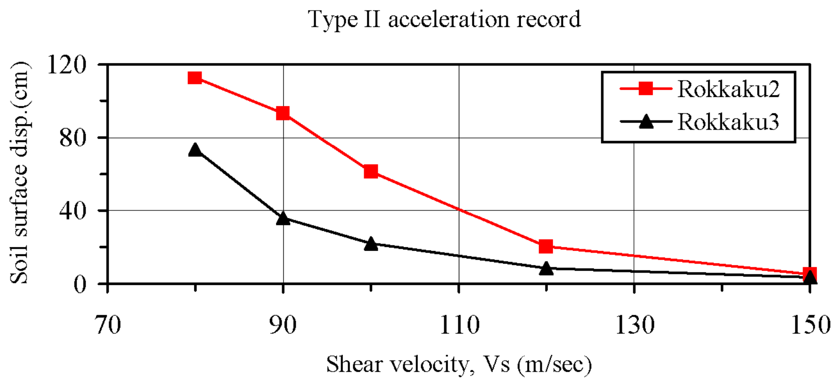

Fig. 17 Effect of strain dependence of rigidity ratio(G/Go) and damping, h (%)

To check the effect of strain dependence of rigidity ratio(*G/Go*) and damping, soil deposit displacement analysis was carried out by using both of the Rokkaku2 and Rokkaku3 curves for various shear wave velocity and the ground displacements are plotted in Fig. 16 and Fig. 17 for different earthquake records. Large difference of soil displacement were obtained between the two curves in the lower range of shear wave velocity. Rokkaku3 curve corresponds to higher rigidity and thus displacement is lower than Rokkaku2. Therefore, it is important that for a given region strain dependence of rigidity ratio(*G/Go*) should be determined by sufficient number of field tests.

Additional analysis using single input model only was carried out for *Vs* of 30, 60 and 250 m/sec to check the effect of soil stiffness change in this model in broader range. Maximum deck displacement and maximum moment in the pile are plotted in Fig. 18 and Fig. 19. Maximum moment distribution along the pile are also plotted in Fig. 20 for *Vs* values of 30, 80 and 250 m/sec. It is observed that in the low shear velocity range, displacement and moment value increase rapidly with decreasing velocity. In the higher shear velocity region maximum moment in the pile increases slowly. For very hard clay, soil in the upper part of the piles behave like fixed support and maximum moment occurred at the pile top (Fig. 20). For very hard clay, upper part of the pile should be heavily reinforced and significant steel bar may be reduced in the lower part based on single input model analysis.

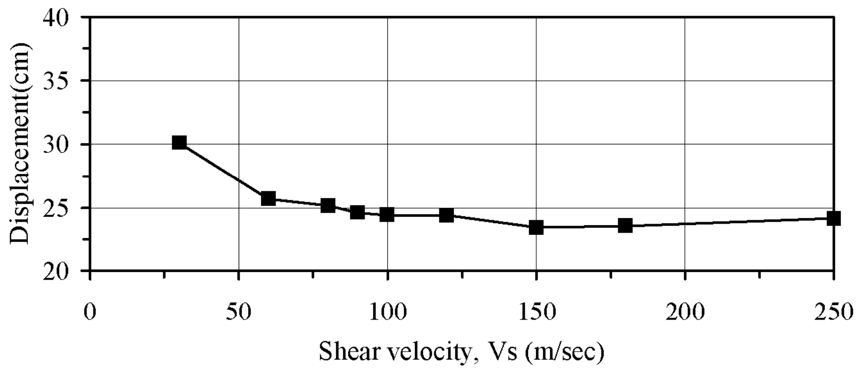

Fig. 18 Single input model – Maximum deck displacement

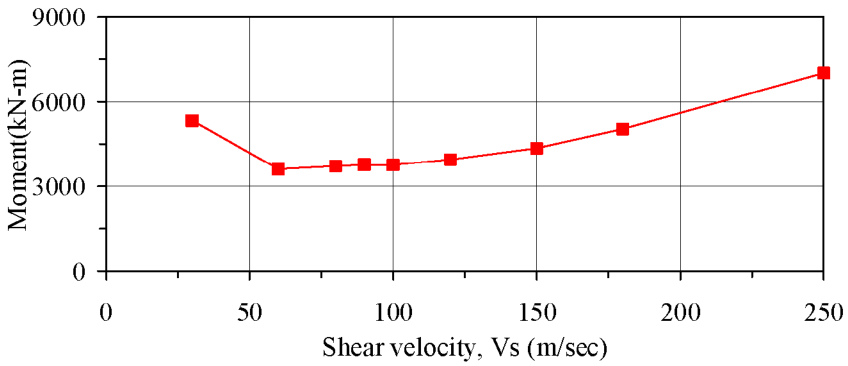

Fig. 19 Single input model – Maximum pile moment

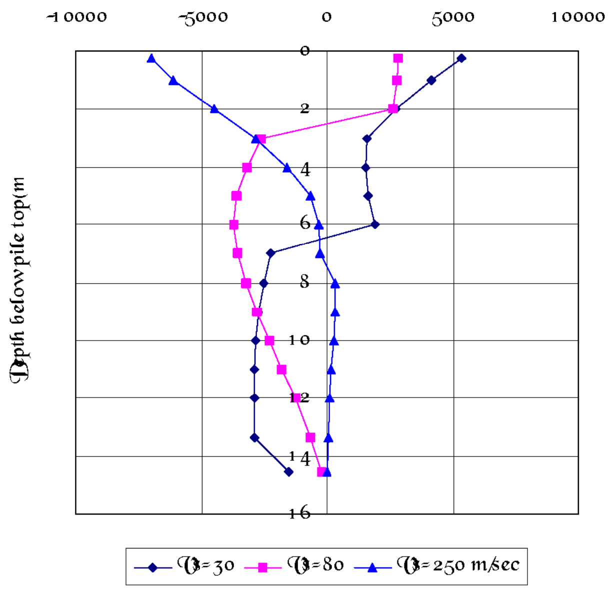

Fig. 20 Single input model – Maximum moment throughout the pile

CONCLUSION

From the results presented above, it can be concluded that with increasing soil stiffness, effect of ground displacement on response of bridge structure with pile foundation becomes smaller in general. For shear wave velocity, *Vs* less than about 100 m/sec, response increases very rapidly. In the low *Vs* region i.e very soft clay, ground displacement has great effect on the response and Penzien model gives much higher value compared to single input model since the former considers ground displacement in the analysis. *Vs* value of 150 m/sec may be considered the critical velocity after which consideration of ground displacement has less effect and the two models yield similar results. Approximately, *Vs* value of 150 m/sec corresponds to soil cohesion value of 60 kPa and N-value of 4 respectively. It is important to increase shear velocity by soil improvement in the very soft zone.

Strain dependence of shear modulus and damping also have significant effect on displacement of the soil deposit and thereby on structural response of the bridge structure based on Penzien model. For harder soil, rigidity is higher and displacement becomes smaller. In the higher shear velocity region, maximum bending moment in the pile slowly increases. For very hard soil, the top region of the pile behaves like fixed support and maximum moment occurs at the pile top. It is recommended that shear velocity be measured accurately by sufficient number of field tests since structural response is greatly dependant on it and also strain dependence of rigidity ratio and damping be measured by field tests similarly.

SESAS program-developed in Saga University Structural System Laboratory can be effectively used for elasto-plastic analysis of pile-soil-superstructure integrated system considering ground displacement.

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