International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

1991 - Second International Conference on Recent Advances in Geotechnical Earthquake Engineering & Soil Dynamics

13 Mar 1991, 1:30 pm - 3:30 pm

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Recommended Citation

Thakkar, S. K.; Mazumdar, D. K.; and Bose, P. R., "Seismic Behaviour of Bridges Considering Soil-Structure Interaction" (1991). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 32.
https://scholarsmine.mst.edu/icrageesd/02icrageesd/session05/32

Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics,
March 11-15, 1991, St. Louis, Missouri, Paper No. 5.47

Seismic Behaviour of Bridges Considering Soil-Structure Interaction

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SYNOPSIS: The soil-structure interaction has significant effect on seismic response of bridges in many situations. The choice of soil springs for response determination is an important consideration. This paper presents a comparative assessment of the seismic response of bridge substructure by four different types of frequency independent soil springs namely, Beredugo-Novak, Wolf, Bycroft-Parmelee and Terzaghi. The variation of equivalent weighted damping and equivalent seismic coefficient is also studied. The Terzaghi's soil springs obtained by modulus of subgrade reaction approach are most flexible as compared to others. The responses are seen to be comparable with springs other than Terzaghi. The equivalent damping in higher modes is increased due to energy dissipation in soil. The codal provisions of equivalent seismic coefficient variation below scour level are generally unconservative.

INTRODUCTION

Bridges form an important transportation link in the highway and railway network of a country. Therefore, safety of the bridge in seismic region is of great importance particularly for post earthquake relief operations. The failure of the bridge substructure and foundation in earthquake is one of the most common cause of damage or collapse of the structure. The influence of soil-structure interaction on the seismic response is still not clearly understood. The main reasons for this are (i) complexity of soil structure interaction effect (ii) difficulties in estimation of stiffness and damping characteristics of soil at great depth under water (iii) lack of comparative studies of analytical and observed seismic response.

The seismic response of bridges founded on alluvial soil is greatly influenced by soil-structure interaction particularly when the ground motion input to the structure is different from that of free field motion of the soil. The interaction that modifies the seismic input due to the presence of the body of structure is further activated by the hetrogenity or non-linearity of the surrounding medium. Therefore, the effect of soil-structure interaction between the embedded bridge structure and the surrounding soil is to be thoroughly investigated for safe and economic design. The main response parameters of structure that are largely influenced by soil-structure interaction are displacement in bridge bearings, cracking of substructure and superstructure, settlement of foundation and design seismic coefficients for embedded portion of substructure. There are no attempts made so far to determine equivalent seismic coefficients below the scour level in bridges. The objectives of this paper are following:

(i) to present comparative assessment of the seismic response of bridge substructure using different types of frequency independent springs

(ii) to study the variation of equivalent damping with embedment for different soil springs

(iii) comparison of variation of horizontal seismic coefficients below the scour level with codal recommendation.

A comparative study for different soil springs is made of time period, shear, moment, deflection, equivalent damping and equivalent seismic coefficient. For the numerical study two simply supported bridges of different spans situated in seismic zone V of India on alluvial soil deposit are selected. The soil springs are calculated from the values of shear modulus and Poisson's ratio of soil.

METHODOLOGY ADOPTED

The substructure of the bridge and its foundation is replaced by a mathematical model as shown in Figure 1. The structural portion consists of beam type elements with lumped mass at discrete points. The discrete masses consist of its own mass, mass of infilled water or sand and the added mass of water to represent hydrodynamic effect. The elastic resistance of a bridge substructure embedded in soil is replaced by the coupled linear and rotational springs at the centre of gravity of the embedded portion. The dead load of superstructure and live load are lumped at the respective centres of gravity.

The method of seismic analysis adopted is well known technique of transfer functions and modal analysis using response spectrum. The method has been documented in the literature (Thakkar, 1982). The dynamic response of the bridge structure is computed by square root of sum of squares (SRSS) method. This enables the computation of dynamic shear, moment and

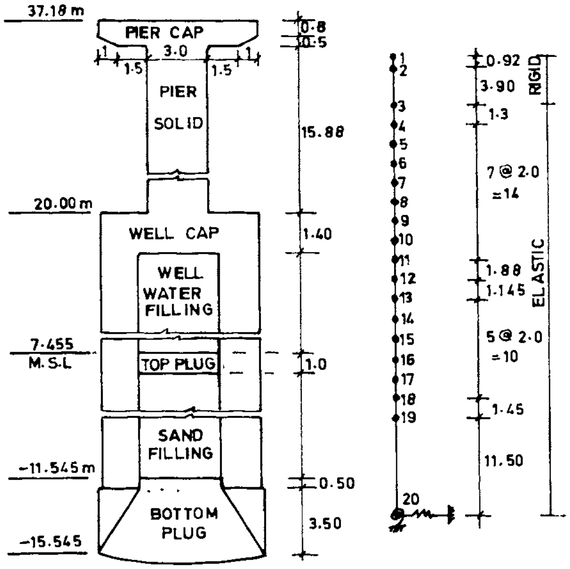

FIG.1 _ SUBSTRUCTURE OF BRIDGE A AND MATHEMATICAL MODEL

deflection in the substructure and foundation. The equivalent seismic coefficient and damping are worked out as follows:

Equivalent Seismic Coefficient

The equivalent seismic coefficient α_h at a node i is obtained from the following expression:

$$\alpha_h = \frac{V_i}{\sum_{i=1}^{n-1} W_i} \qquad (1)$$

where, V_i = dynamic shear just above node i and W_i = weight at the node i.

Equivalent Damping

The equivalent damping ζ_{eq} in a mode is worked out on the basis of stored strain energy in a mode by the following expression:

$$\zeta_{eq} = \frac{\zeta_s U_s + \zeta_t U_t + \zeta_r U_r}{U_s + U_t + U_r} \qquad (2)$$

where, ζ_s, ζ_t and ζ_r are viscous damping damping factors in structure, translation and rotation in soil respectively; U_s, U_t and U_r are strain energy stored in a mode in structure, translation in soil and rotation in soil respectively.

SOIL SPRINGS

The embedded portion of foundation is replaced by coupled linear and rotational springs at the centre of gravity of embedded portion. The frequency independent foundation impedence matrix is represented as follows:

$$K_f = \begin{bmatrix} K_{xx} & K_{x\theta} \\ K_{x\theta} & K_{\theta\theta} \end{bmatrix} \qquad (3)$$

where, K_{xx}, $K_{x\theta}$ and $K_{\theta\theta}$ are linear, coupled and rotational spring constant of foundation. The soil springs considered in this study are: (i) Beredugo-Novak (1972), (ii) J.P. Wolf (1988), (iii) Bycroft-Parmelee (1974), and (iv) Terzaghi (1955).

Beredugo-Novak Spring

The Beredugo-Novak springs are based on elastic-half space layer and elastic side layer resting over the base layer. The buried portion of structure is considered to be rigid and cylindrical. The spring constants are given as follows:

$$K_{xx} = Gr_o(4.78 + 4.033G_r\delta)$$
$$K_{x\theta} = -Gr_o[4.78Z_c + 4.033\,G_r\,\delta(Z_c-0.5L)]$$
$$K_{\theta\theta} = Gr_o^3[2.5+4.78\,Z_r^2 + 2.5G_r\delta + 4.033\,G_r\,\delta\left(\frac{\delta^2}{3} + Z_r^2 - \delta Z_r\right)] \qquad (4)$$

where, G and G_s are shear modulus of base and side layer respectively, r_o = radius of foundation, L = depth of embedment, Z_c = distance of centre of gravity of foundation from base, $\delta = L/r_o$, $G_r = G_s/G$, $Z_r = Z_c/r_o$.

Wolf Spring

The Wolf spring is based on cylindrical structure embedded in homogeneous elastic half space. The buried portion is considered to be rigid. The frequency independent spring constants are given as follows:

$$K_{xx} = \frac{8Gr_o}{2-\nu}(1+\delta)$$
$$K_{x\theta} = \frac{8Gr_o^3}{3(1-\nu)}(1 + 2.3\delta + 0.58\delta^3)$$
$$K_{\theta\theta} = \frac{8Gr_o}{2-\nu}(1+\delta)\,0.25\,L \qquad (5)$$

where, G and ν are shear modulus and Poisson's ratio of foundation soil respectively.

Bycroft-Parmelee

The stiffness of springs for surface footing are considered from Bycroft (1956) and effect of embedment are considered from Parmelee (1974). In Bycroft expression, the foundation is a rigid circular section resting on a semi-infinite elastic half space. The Bycroft and Parmelee expressions are thus combined and these are called Bycroft-Parmelee springs. Embedment coefficient derived by Parmelee is applicable to rectangular section. In this analysis the embedment effect is modified for circular section by considering equivalent radius concept. The spring constants are given as follows:

$$K_{xx} = \Delta_h K_t$$
$$K_{\theta\theta} = \Delta_r K_r$$
$$K_{x\theta} = 0.0 \qquad (6)$$

where,

$$K_t = 4.4\,Gr_o$$
$$K_r = 2.3\,Gr_o^3 \qquad (7)$$

Δ_h and Δ_r are embedment factors for horizontal and rocking stiffness:

$$\Delta_h = 1 + 2.412\delta + 0.7703\delta^2 + 0.3183\delta^3 + 0.0989\delta^4$$
$$\Delta_r = 1 + 2.556\delta + 0.7883\delta^2 + 0.3302\delta^3 + 0.1036\delta^4 \qquad (8)$$

Terzaghi Spring

The modulus of subgrade reaction method (Terzaghi, 1955) for obtaining soil springs is employed for cohesionless soil. The soil modulus value increases linearly with the depth. The soil springs are worked out at centre of gravity of embedment depth.

$$K_{xx} = \frac{2}{\Delta_v + C\Delta_m}$$
$$K_{\theta\theta} = \frac{(2C + L)}{2(\theta_v + C\theta_m)} \qquad (9)$$

where, $\Delta_v = L/D_1$; $\theta_v = 1/D_1$; $\Delta_m = 1/D_1$;

$$\theta_m = 1/LD_1$$

$$D_1 = n_h L^3/12 + \frac{2}{3}\frac{K_v r_o^3}{L} + \mu n_h L^2 r_o/6 \qquad (10)$$

where, $C = M_o/V_o$, M_o and V_o are moment and shear acting on the top of embedded portion, n_h = soil modulus in t/m^3, μ = coefficient of friction, K_v = vertical modulus of subgrade reaction, Δ_v, Δ_m = deflection of well at top due to unit shear and moment respectively; θ_v and θ_m are slope of well due to unit shear and unit moment respectively.

The damping constants of Beredugo-Novak, Wolf, Bycroft-Parmelee are not considered for equivalent damping evaluation, instead equivalent weighted damping concept has been used with all the types of springs.

DESCRIPTION OF BRIDGE

Structural Data

For the purpose of numerical study two simply supported bridges of different spans situated in zone V of India (IS:1893-1984) have been selected. The simply supported bridges have roller and rocker bearings at their ends. The structural data of bridge is shown in Table I. The cross sectional details of both the bridges are similar. The cross-sectional detail of bridge A and its mathematical model in transverse direction are shown in Fig. 1.

TABLE I. Structural Data of Bridges

Item	Bridge A	Bridge B
span (m)	7x31.26 + 2x13.10	4x64.0+2x63.85+19.90
superstructure	steel truss	steel truss
pier	single solid circular concrete pier	single rcc circular hollow pier
well	8.0m diameter hollow circular rc wells	10.0m diameter hollow circular rc wells
Height from base to the top of pier (m)	52.725	62.325
depth of embedment (m)	23.0	28.30

Other Input Data

Soil data : The details of soil data for the bridges are given in Table II.

TABLE II. Soil Data of Bridges

Bridge	Base Shear Modulus t/m^2	Side Shear Modulus t/m^2	Poisson's Ratio	Soil Modulus n_h (Terzaghi) t/m^3
A	20500.0	5300.0	0.30	1080.0
B	26000.0	6010.0	0.30	1080.0

Damping data : The structural damping is assumed to be 5%, the translational damping in soil as 20.0% and rotational damping in soil as 7%.

Response spectrum : The response spectrum of site for 5% and 10% damping is shown in Fig. 2.

Hydrodynamic pressure : The virtual mass of water around submerged pier-well has been considered using cylinder analogy method (IS:1893-1984).

Live load : The live load as per codal practice is considered under seismic conditions (IS:1893-1984).

Impedence functions : The four different types of frequency independent springs as described above are used here.

RESULTS AND DISCUSSIONS

The dynamic analysis of two bridges has been carried out using four different soil springs. The comparisons are made for time periods, mode shapes, dynamic structural response, viz shear,

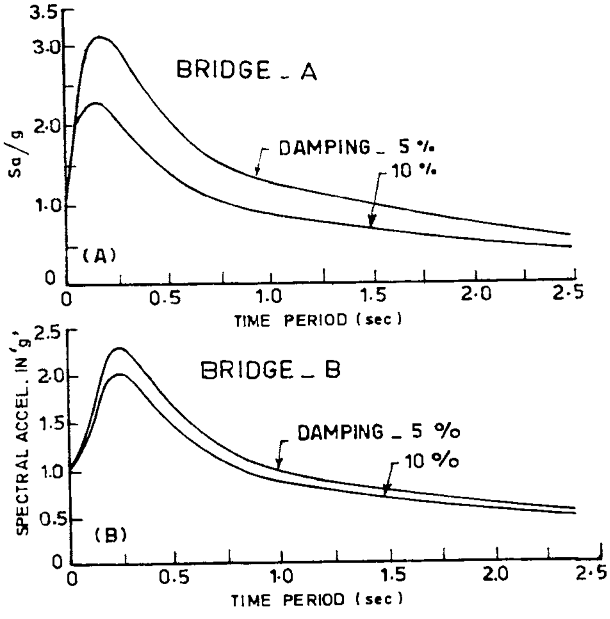

FIG. 2 _ ACCELERATION RESPONSE SPECTRUM

moment and deflection, equivalent seismic coefficient and equivalent damping. The Beredugo-Novak springs are considered as basis for comparison. The results of dynamic analysis for different soil springs are discussed below.

Natural time periods and Mode shapes

TableIII shows a comparison of time periods for three modes of vibration for two bridges A and B. The variation of fundamental periods are 8 to 23% for different springs except Terzaghi springs which overestimates the period by 74-123% as compared to Beredugo-Novak method. The time periods obtained by Wolf and Bycroft-Parmelee spring are close to each other. Terzaghi's spring is the most flexible one among all other springs followed by Beredugo-Novak, Wolf, and Bycroft-Parmelee.

Figure 3 shows the mode shapes for different springs. The mode shapes using Terzaghi spring shows rigid body behaviour of structure unlike other springs, this is because of flexible nature of Terzaghi spring.

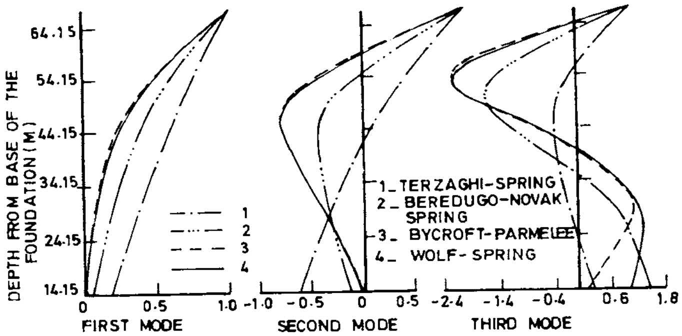

FIG.3_MODE SHAPE OF BRIDGE B IN TRANSVERSE DIRECTION

Bending moment, Shear force and Deflection

Figures 4a, b, and c shows the variation of bending moment, shear force and deflection distribution along the height for different springs in bridge B. It can be noted that Terzaghi spring gives bending moment about 28% lower than the Beredugo-Novak springs. The deflections obtained in Terzaghi spring are much larger than for other springs.

Equivalent seismic coefficient

Figure 4d shows the variation of equivalent seismic coefficient along the height. It can be seen that seismic coefficient with Terzaghi spring give much lower values. This is because of long periods of vibration.

Figure 5 shows the comparison of seismic coefficient below scour level between IS:Code and Beredugo-Novak springs. It can be observed that codal provisions are generally unconservative as compared to results of dynamic studies.

Equivalent damping

The values of equivalent damping in first three modes for bridges A and B are presented in Table 4. The equivalent damping obtained with Terzaghi's spring is larger as compared to other springs. The damping in the first mode is governed by the structural damping, the contribution of soil damping is clearly seen in second and third modes.

TABLE III. Time Periods (second) of Bridges in Transverse Direction

Soil Spring	Bridge A			Bridge B		
	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3
Beredugo-Novak	0.759	0.343	0.101	0.724	0.291	0.111
Wolf	0.686	0.228	0.081	0.562	0.225	0.079
Bycroft-Parmelee	0.686	0.226	0.078	0.562	0.222	0.068
Terzaghi	1.322	0.619	0.326	1.621	0.664	0.262

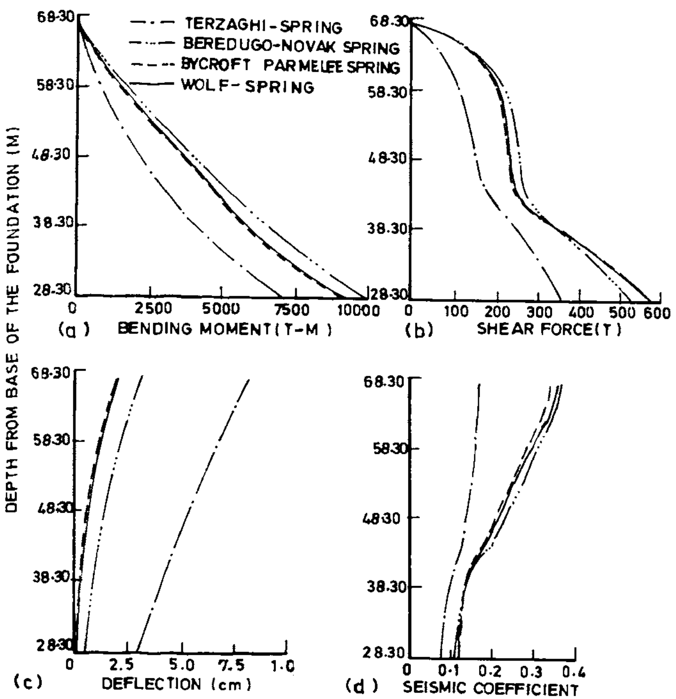

FIG. 4_ B.M., S.F., DEFLECTION AND SEISMIC COEFFICIENT FOR BRIDGE 'B'

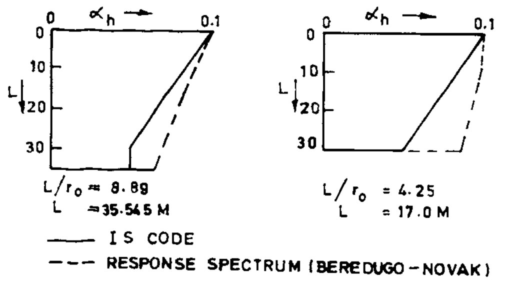

FIG. 5_EQUIVALENT SEISMIC COEFFICIENT BELOW SCOUR LEVEL FOR BRIDGE A

TABLE IV. Equivalent Viscous Damping Factor in Transverse Direction

Soil Spring	Bridge A			Bridge B		
	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3
Beredugo-Novak	0.60	0.087	0.128	0.073	0.079	0.138
Wolf	0.050	0.058	0.079	0.051	0.058	0.136
Bycroft-Parmelee	0.050	0.052	0.050	0.051	0.051	0.051
Terzaghi	0.103	0.130	0.083	0.112	0.148	0.057

CONCLUSIONS

This paper presents the study of response of bridge substructure when the foundation is idealized using different types of frequency independent springs. The following conclusions are drawn from this study:

1. The soil springs obtained by modulus of subgrade reaction approach are the most flexible among the four springs used in the analysis.

2. The Beredugo-Novak spring gives somewhat larger responses as compared to spring of Wolf and Bycroft-Parmelee. The responses are seen to be comparable with springs other than Terzaghi.

3. The equivalent damping is increased in higher modes due to energy dissipated in soil.

4. The equivalent seismic coefficient variation in the embedded portion obtained by dynamic analysis is more than that obtained by IS:Code.

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