TRAVELLING WAVES IN A GROUP OF PILES TAKING PILE-SOIL-PILE INTERACTION INTO ACCOUNT

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Summary: A reactor building founded on piles is analysed for a horizontally propagating historic earthquake taking pile-soil-pile interaction into account. In general, a larger response results than that for vertically incident waves.

For a structure founded on piles, it is important to take pile-soil-pile interaction into account (group effect). To study the effect of horizontally propagating waves on a group of piles, the response of a reactor building founded on 101 piles of diameter 1.70 m (Fig. 1), situated in a layered site (Fig. 2), is calculated. The numerical procedure of Refs. [1,2] is adapted. The J145 record of the 1971 San Fernando earthquake is used as the free-field motion at the surface. Plotting the vertical versus the radial (horizontal) component of the displacement (Fig. 3), the retrograde motion, which can be associated with R-waves, is apparent (Ref. [3]). The apparent velocity c is varied parametrically.

As can be seen from the free-field response of the site for harmonic excitation propagating along the bedrock, the largest horizontal amplification (for inclined body waves) arises at quite low apparent velocities for certain frequencies (Fig. 4b). A substantial vertical motion also results (Fig. 4c). The horizontal response of a single pile embedded in the same soil layer is similar to that of the free field (Fig. 5a). The peak-response frequency for $c = 250$ m/s is larger than the fundamental frequency of the soil layer (2.91 Hz). Because of the self-cancelling effect of the travelling wave, this peak amplitude is significantly reduced when compared to that for vertical incidence ($c = \infty$), and the horizontal displacement at the pile head is strongly diminished for higher frequencies. For $c = 100$ m/s (angle of incidence of S-wave less than critical angle), the amplitude is less than 1.0 for all frequencies.

The amplitudes at bedrock (free-field) show minima at the horizontal frequencies of the soil layer for vertically incident waves (Fig. 6a). As the short piles are quite stiff, the amplification from bedrock to the (rigid) basemat is small for kinematic interaction (structure without mass). The amplitude at basemat corresponds to the horizontal displacement of $\{q_o\}$ in Eq. 19 of Ref. [2]. For $c = 250$ m/s, the amplitudes at bedrock are reduced and the minima appear at somewhat larger frequencies (Fig. 6b). Again, the travelling-wave effect reduces the amplitude at basemat drastically in the intermediate- and higher-frequency range (solid line) as compared to the corresponding value for $c = \infty$ (dotted line). The vertical acceleration of the basemat (kinematic interaction) resulting from the hor-

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izontally propagating wave along the surface (Fig. 2) exhibits smaller amplitudes and less high-frequency content than the vertical component of J145 (Fig. 7a). Intermediate frequencies are present in the corresponding rocking acceleration (Fig. 7b). These effects of travelling waves are confirmed in the corresponding response spectra (Fig. 8). For vertically incident waves, some high-frequency content is still present (dotted line).

The structural response in the vertical direction is reduced for the horizontally propagating earthquake record J145 (Table 1). However, the induced rocking input, counteracted by the decreased horizontal component, results in significantly larger horizontal accelerations, overturning moment and shear force of the pile group. Pile-soil-pile interaction leads to larger forces (Table 2) in the piles at the boundary than in those in the centre (Fig. 1). As horizontally travelling waves lead to higher stresses in the soil, the pile forces from kinematic interaction are more important than for vertical incidence. While for c = ∞ a good approximation of the maximum total pile forces can be determined, assuming the corresponding value of kinematic and inertia interaction to be statistically independent, the same no longer applies for c = 250 m/s. As expected, the larger overturning moment results in significantly larger normal forces in the boundary pile for travelling waves. The significant rocking input (Fig. 8b) present at the first and second frequencies of the soil-structure system (2.16 Hz, 4.46 Hz) leads to a drastic increase in the in-structure response spectra (Fig. 9). In general, travelling-wave effects govern the design of the piles, the structure and the equipment located within.

Apparent Velocity [m/s]			c = 250	c = ∞
Total Accelerations [g]	Seismic Input	Horizontal	0.081	0.088
		Vertical	0.049	0.073
		Rocking * r	0.047	0.000
	Top Pressure Vessel	Horizontal	0.380	0.216
		Vertical	0.051	0.082
	Top Shield Building	Horizontal	0.438	0.200
		Vertical	0.052	0.114
	Basemat	Horizontal	0.240	0.154
		Vertical	0.050	0.079
Shear Force of Pile Group		[MN]	186.7	119.4
Overturning Moment of Pile Group		[GN m]	4.3	2.7
Vertical Force of Pile Group		[MN]	36.6	64.3

Table 1 Maximum Response of Reactor Building

Apparent Velocity [m/s]		c = 250			c = ∞		
		Inertia Interaction	Kinematic Interaction	Total	Inertia Interaction	Kinematic Interaction	Total
Shear Force [MN]	Centre Pile	1.704	0.368	1.926	1.088	0.124	1.144
	Boundary Pile	2.050	1.232	2.790	1.310	0.157	1.379
Bending Moment [MN m]	Centre Pile	7.908	1.194	8.659	5.051	0.958	5.486
	Boundary Pile	8.365	4.950	11.423	5.344	0.436	5.545
Normal Force [MN]	Centre Pile	0.364	--	--	0.631	--	--
	Boundary Pile	7.466	--	--	4.666	--	--

Table 2 Maximum Forces at Pile Heads

[1] J.P. Wolf, G.A. von Arx, Impedance Function of a Group of Vertical Piles, Proc. Geotechn. Eng. Div. ASCE Spec. Conf. on Earthq. Eng. and Soil Dynamics, June 1978, pp 1o24-41

[2] J.P. Wolf, Dynamic Stiffness of a Group of Battered Piles, J. of the Geotechn. Eng. Div., ASCE, Feb. 1980

[3] J.P. Wolf, P. Obernhuber, Effects of Horizontally Travelling Waves in Soil-Structure Interaction, to be published in Nucl. Eng. Des.

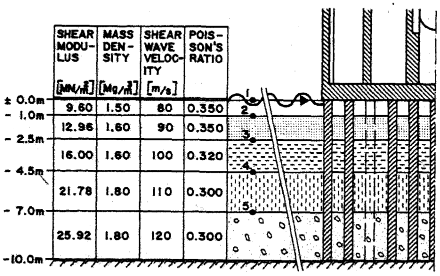


Fig. 2 Free-Field Properties of Soil Layer

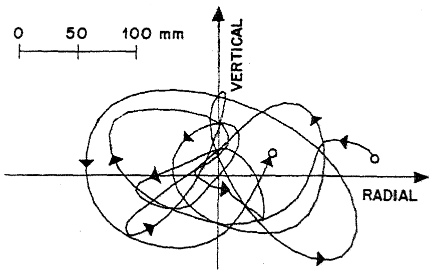


Fig. 3 Vertical versus Radial Displacement, San Fernando Earthquake, Corrected Record J145, 10s - 28s

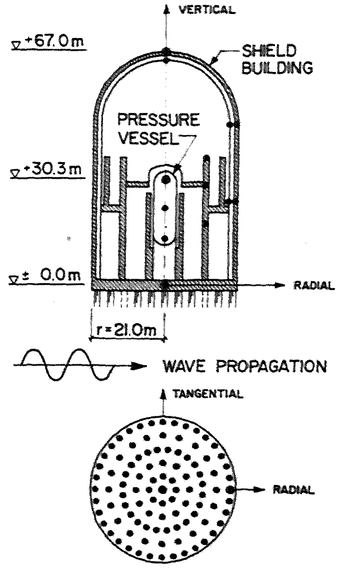
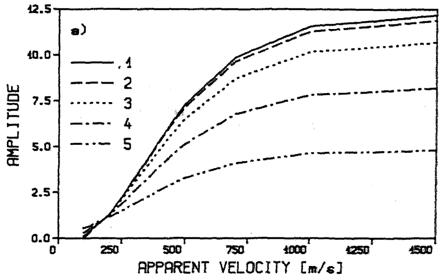


Fig. 1 Dynamic Model of Reactor Building, Elevation and Plan View with Location of Piles



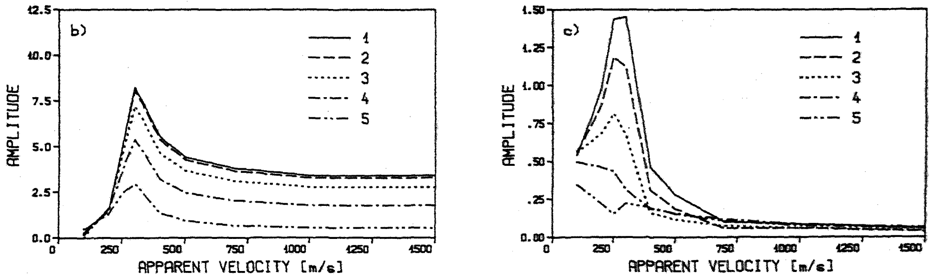


Fig. 4 Amplitude of Displacement in Various Points of Free Field Resulting from Horizontal Harmonic Displacement of Unit Amplitude at Bedrock versus Apparent Velocity a) Horizontal Displacement, Frequency 2.91 Hz b) Horizontal Displacement, Frequency 3.60 Hz c) Vertical Displacement, Frequency 3.60 Hz

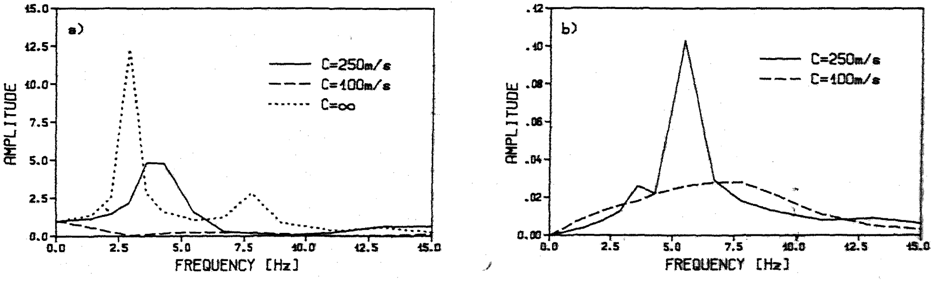


Fig. 5 Amplitude of Displacement at Head of Single Pile Resulting from Horizontal Harmonic Displacement of Unit Amplitude at Bedrock versus Frequency a) Horizontal Displacement b) Vertical Displacement

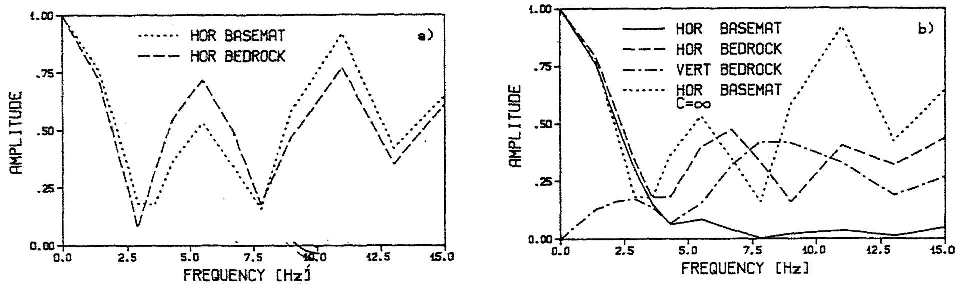


Fig. 6 Amplitude of Displacement at Bedrock and Basemat Resulting from Horizontal Harmonic Displacement of Unit Amplitude at Surface versus Frequency (Kinematic Interaction) a) c = ∞ b) c = 250 m/s

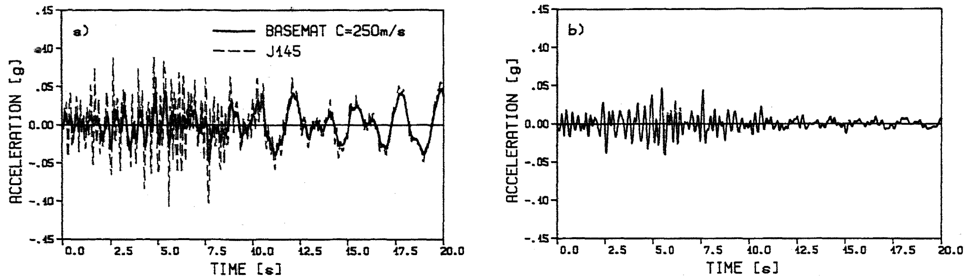


Fig. 7 Time-History of Seismic Input Motion a) Vertical Acceleration at Surface of Free Field and at Basemat Resulting from Kinematic Interaction (c = 250 m/s) b) Rocking Acceleration x r at Basemat Resulting from Kinematic Interaction (c = 250 m/s)

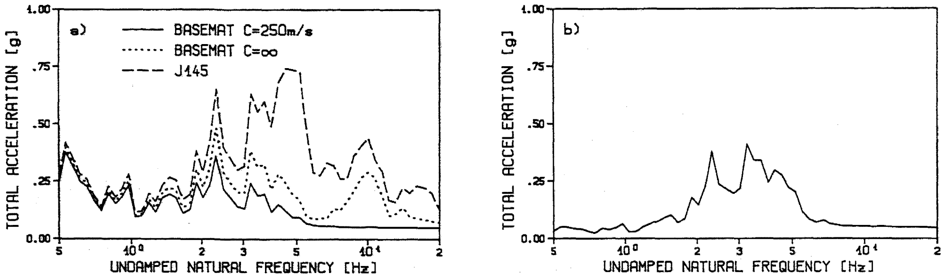


Fig. 8 Response Spectra (1% Damping) of Seismic Input Motion a) Vertical Acceleration at Surface of Free Field and at Basemat Resulting from Kinematic Interaction (c = 250 m/s and c = ∞) b) Rocking Acceleration x r at Basemat Resulting from Kinematic Interaction (c = 250 m/s)

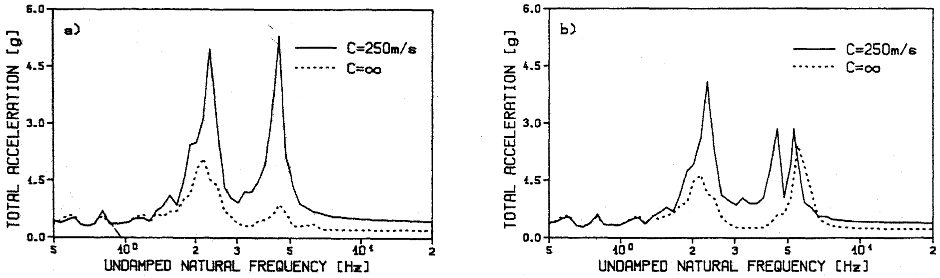


Fig. 9 In-structure Response Spectra (1% Damping), Horizontal Acceleration a) Top Shield Building b) Top Pressure Vessel