V SUMMARY AND CONCLUSIONS

In this report, an analysis of the response of base isolated buildings is presented, in the frequency domain. The model is two-dimensional and linear. The building is represented either by an equivalent SDOF oscillator or by a shear beam supported by elastic rubber bearings. The stiffness of the bearing is taken to be the elastic stiffness of realistic elastomeric bearings. (In this analysis, it is assumed that typically the stiffness of the base isolated building is one quarter of the stiffness without base isolation). The coupling of the vertical accelerations with the horizontal translation and the rocking are neglected. The behavior of the base isolated models is first analyzed excluding the soil-structure interaction, then including only inertia interaction, and at the end including also the wave passage effects. It is also studied whether and under what conditions various approximations of the input motion (such as horizontal driving motion of the foundation or a combination of horizontal and rocking driving motions, excluding and including the soil-structure interaction) are adequate.

The results of the study using a SDOF equivalent oscillator for the building can be summarized as follows.

1. *Fixed Base Model.* If the platform is massless ($m_p/m_b \to 0$), and the building is slender so that $r_b/H \to 0$, the model has only one natural frequency, ω_{eq}, such that $\frac{1}{\omega_{eq}^2} = \frac{1}{\omega_N^2} + \frac{1}{\omega_i^2}$. If the platform has mass (m_p/m_b), and the building is slender ($r_b/H \to 0$), the model has two natural frequencies, ω_1^* and ω_2^* ($\omega_1^* < \omega_2^*$) that can be evaluated analytically (Eq. (III.2)). If the platform is massless ($m_p/m_b \to 0$), but the building is not slender ($r_b/H \neq 0$), the transfer-function of $u_b^{\mathrm{rel}} = \psi^{\mathrm{rel}} H$ also has two peaks. In the more general case, when $m_p/m_b \neq 0$ and $r_b/H \neq 0$, the transfer-function of u_b^{rel} has two peaks. The peak frequencies are such that $\omega_1^* < \omega_N < \omega_2^*$. Both peaks of base isolated building have lower amplitude than peak amplitude for the same building on rigid isolators.

2. *Flexible Base Model, the Wave Passage Effects Ignored.* When the model is on soft soil and dynamic soil-structure interaction takes place (the input motion is a horizontal translation of the base only), the system frequencies $\overline{\omega}_1^*$ and $\overline{\omega}_2^*$ are lower than the corresponding fixed-base frequencies ω_1^* and ω_2^*. For the three and six story buildings analyzed, the soil-structure interaction further reduced the amplitudes of the peaks of the transfer-function, while for the ten story buildings the additional beneficial effect of the dynamic soil-structure interaction, in terms of further reduction of the peak amplitudes of the transfer-function of u_b^{rel}, was not seen.

3. *Effects of the Wave Passage.* As a result of the wave passage, the foundation input motion contains a rocking component (even for vertically incident SV-waves, because of the foundation embedment). The amount of input rocking excitation, per unit amplitude of the horizontal component of the free-field motion, is the largest for incident P waves and incident SV-waves beyond critical angle. The amplitude of the input rocking depends on the ratio of the width of the foundation and the S-wavelength in the soil. For example, for incident Rayleigh waves the input rocking is the largest when this ratio is 0.5. For

very long incident waves, compared with the size of the foundation, the input rocking goes to zero. For the example buildings (three, six and ten story buildings), the additional input rocking amplifies more the higher frequency peaks in the transfer-function of u_b^{rel}. For incident SV-waves beyond critical angle, and for Rayleigh waves, the higher frequency peak has larger amplitude than the lower frequency peak, while it is the opposite when the wave passage effects are ignored. Moreover, the transfer-function of u_b^{rel} may have higher amplitude away from the two system frequencies, which is the case for the six and then story buildings subjected to incident Rayleigh waves. The point rotation on the half-space surface can approximate the foundation input motion only for very long wavelengths of the incident waves. Otherwise, it overestimates the response amplitudes and the results are not meaningful. The free-field point rotation can be used only to estimate the amplitude of the lower frequency peaks in the transfer-function of base isolated buildings.

The analysis of the model with a shear beam representing the building showed the following.

The frequencies and the response amplitudes for the higher modes are not much affected by the inertial interaction.

1. *Fixed Base Model* The characteristic equation for the base isolated shear beam on rigid soil and in the absence of viscous damping is a transcedental equation. For high frequencies, if the platform is massless, the characteristic frequencies approach those of a free-free shear beam, and if it does have mass, those of a fixed-base shear beam.

2. *Flexible Base Model, the Wave Passage Effects Ignored.* When the platform has mass, the first and second modes correspond to the first and second modes of the base isolated SDOF oscillator, and are affected by the soil-structure interaction in a similar fashion. The higher order peaks are affected little by the inertial interaction, both in terms of change of the modal frequencies and of amplitudes. For hard and medium hard soil, the overturning moment about the foundation center is smaller for the second mode than for the first and third modes. The amplitudes of the higher modes do not depend much on the stiffness and damping of the base isolators, or on the stiffness of the soil.

3. *Effects of the Wave Passage.* The second mode is more excited by the rotation of the foundation input motion than the other modes. For a fixed base model, the first three peaks of the relative response on the top, the shear force at the base of the shear beam and the overturning moment about point O are consistently smaller, when the base isolators are more flexible. However, due to the foundation input rocking, the second and third peaks may have larger amplitude, when the base isolators are more flexible. Even for the higher modes, the foundation input motion, when having sufficiently large amplitudes, has a significant contribution to the overall system response.

4. *Comparison of the Responses for the Five Loading Cases.* Three factors influence the response amplitudes: (a) the inertial interaction, which affects significantly only the first, second and maybe third peaks, (b) the amplitude of the free-field point rotation, which depends on the type of incident waves and angle of incidence, and increases linearly with frequency, and (c) the wave passage effects, in the sense of a particular combination of

amplitude and phase of the foundation input translation and rotation. Therefore, which factor is predominant depends on the frequency window and type of incident waves and on the angle of incidence. Factor (c) is most significant for the incident Rayleigh waves.

It can be concluded that the soil-structure interaction and the wave passage effects may significantly influence the response of base isolated buildings, and therefore must be considered in the design of the bearings. The analysis in this report is only linear. For elasto-plastic bearings, these effects may be even more pronounced, and there may be other important effects due to coupling of the vertical accelerations with the horizontal and rocking motions, such as instability. The purpose of this report is to point out some of the effects usually ignored in practice. All of these must be examined in more detail for more realistic models of the building, base isolators and soil-structure interaction models.