SEISMIC RESPONSE OF FROZEN - THAWED SOIL SYSTEMS

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SYNOPSIS

Whereas considerable research has been devoted to measurement of the dynamic properties of frozen soils, little emphasis has been placed on possible effects of a frozen soil layer when a soil profile is subjected to earthquake motions. In this paper some estimates of the basic dynamic performance of frozen soils in earthquakes are made by use of parametric studies. These show that a shallow frozen layer can significantly affect the anticipated motion at the ground surface.

INTRODUCTION

In the early design stages of the Trans-Alaska Pipeline Project, some consideration was given to the effects of the seasonally frozen soil layer and the motion produced in a buried pipeline during an earthquake. Some preliminary studies were made before design changes occurred which precluded burial in frozen ground in the more seismic areas of the route. Research studies showed a shortage of data on dynamic properties of frozen soils and an almost total lack of estimates of the response of these soils when subjected to earthquake loadings.

Initial studies relied heavily on data by Kaplar (1969). This has since been augmented by other investigators including Roethlisberger (1972), Stevens (1975), and Vinson and Chaichavong (1976). Experimental data on frozen soils has shown that whereas the elastic properties are higher by approximately two orders of magnitude, the strain dependent characteristics are similar to those for non-frozen soils. Damping ratios for frozen and unfrozen soils are approximately equivalent.

DYNAMIC SOIL PROPERTIES

Using the referenced data, the set of curves shown on Figure 1 & 2 have been prepared to represent the variation of shear modulus and damping at different strain levels for a gravelly sand with an unfrozen relative density of approximately 70 percent. The modulus curves are developed principally from data presented by Vinson and Chaichavong. The modulus of frozen soils is little affected by confining pressure but is quite sensitive to water content and the degree of saturation. The shear modulus of frozen soils is very sensitive to temperature. The data on Figure 1 shows modulus values for temperatures of -1^{o}, -4^{o}, and -10^{o} centigrade. Damping is not very sensitive to temperature effects as can be seen from the damping curves shown on Figure 2. Experimental data suggests that the damping mechanism in frozen soils may be partially of the viscous type and is therefore more sensitive to the frequency of loading than are thawed soils.

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OBSERVED EFFECTS

The 1964 Prince William Sound Earthquake in Alaska provided numerous indications of the damaging effects of seismic shaking in frozen soils. Ground cracking without permanent horizontal displacement was generally believed to be the result of brittle fracture of the surficial seasonally frozen soils. These failures of the frozen soil persisted as features which could be observed after the earthquake. In many areas it could be verified that these fissures were due to surface flexure rather than to later movements related to incipient landsliding. The surface flexures in Valdez which were observed by Clark and described in Coulter & Migliaccio (1966) had a wave length of approximately 800 feet and a peak-to-peak amplitude of about 4 feet. These produced numerous fractures. This observed flexture motion implies a maximum dynamic strain of approximately 0.8 percent which would be sufficient to produce fracture of the frozen soils. An evaluation of ground response in Valdez by shear wave propagation procedures gave shear wave velocities and wave lengths that are in good agreement with the observations. It is believed therefore that useful preliminary parametric studies of the effects of a frozen surface layer and site response can be obtained using shear wave propagation procedures.

SOIL PROFILES MODELLED

The most extensive soils encountered along the Trans-Alaska Pipeline route consist of sands and gravels of both glacial and alluvial origin. Therefore, simple profile consisting of a gravelly sand with an unfrozen relative density of 70 percent with a shallow water table was used for the analyses.

ANALYTICAL RESULTS

The effects of varying frozen soil thicknesses on the compute peak acceleration was examined first. The input motion for the studies was a synthetic time history taken from a set of time histories which had an average response spectra closely approximating the Newmark, Hall & Mohraz recommendations (1975). The attenuation effects produced by the frozen layer are shown in Figure 3. In this figure the ratio between the peak acceleration for a profile with differing depths of seasonal freezing and the peak acceleration for a fully thawed profile is shown for 3 profiles with different total depths. The frozen thickness was taken to a maximum of 25 feet. This is probably somewhat greater than the seasonal freeze depth in most areas of Alaska. On the basis of studies for this simple model, the effect of the frozen soil has been shown to reduce the peak acceleration by up to 40 percent in the shallowest profile. The existence of an irregular freeze front could be expected to increase this attenuation effect by the frozen surface soils.

Spectral values are a much more reliable measure of the attenuation demonstrated in Figure 3. The effects of the motion attenuation on the response spectra value at a period of 0.5 seconds is shown on Figure 4. The maximum spectral reduction in Figure 4 is somewhat smaller than that shown for the peak acceleration in Figure 3 but the trends demonstrated by peak acceleration only are closely followed.

OTHER EFFECTS

Seismic response of other conditions produced by the Trans-Alaska Pipeline have also been studied. Highway and other construction in the delicate arctic environment can result in a condition where the environmental change will produce degradation of the permafrost. In such cases the thawfront advances slowly each season and can produce an elongated thawed zone which may be up to 50 feet in depth. Because of the concern for the stability of the soils in this thawed zone especially in the longitudinal direction, some studies were undertaken. These required development of special finite element techniques where the motion was applied normal to the finite element mesh. This technique was described by Rukos (1971) and some results from analyses have been published by Donovan (1975). Seismic stability of soils on slopes can be affected by the moisture conditions including the type of ground ice and pore pressures developed at the advancing thawfront.

There are many additional aspects of seismic behavior of soils which must be considered where soil conditions include a thawed and frozen environment. The use of resources in such difficult climates require that these effects be studied in advance of developments so that extensive construction difficulties and environmental damage can be minimized.

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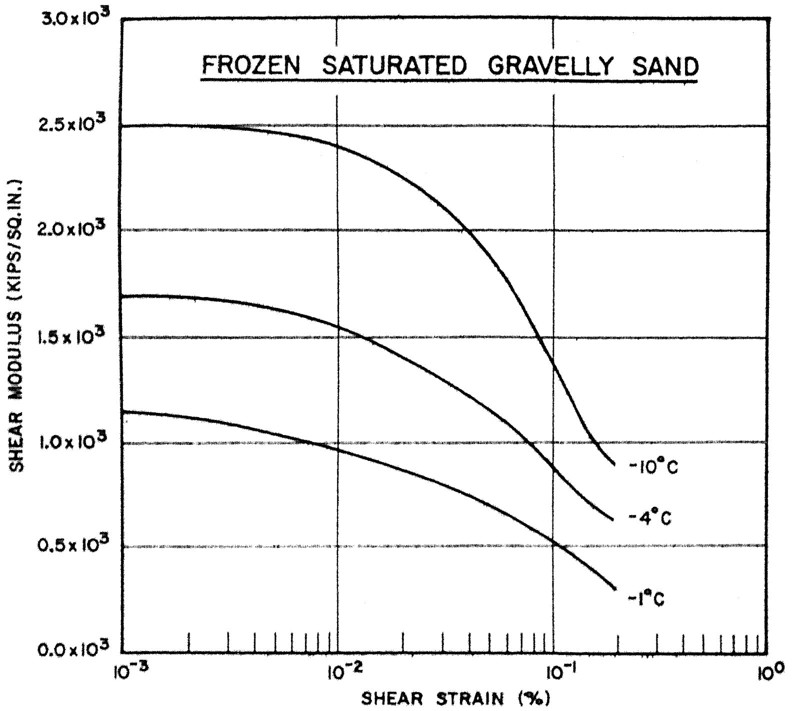
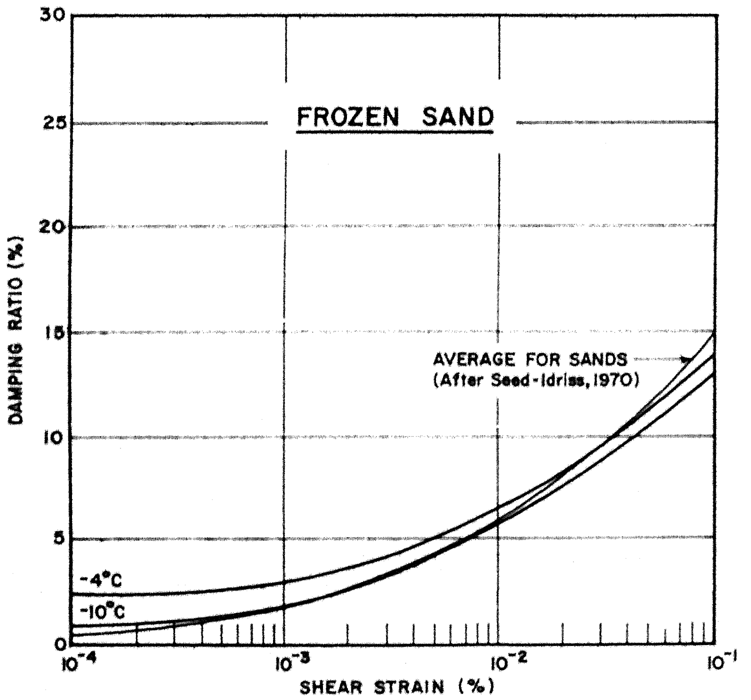


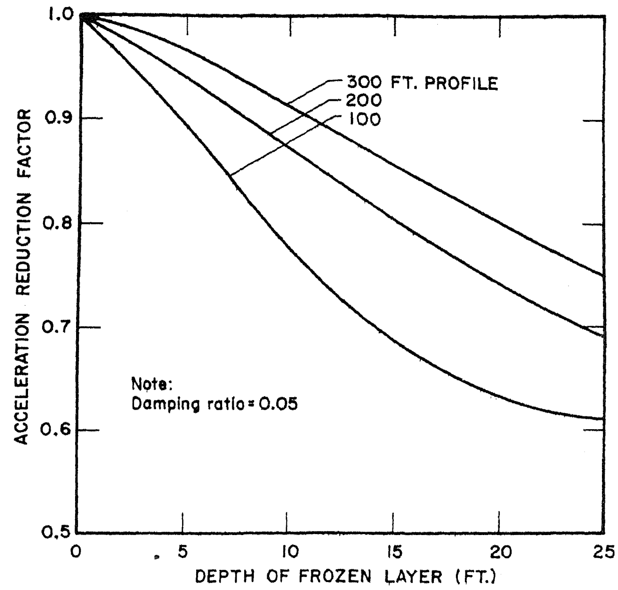
SHEAR MODULUS OF FROZEN SAND

Fig. 1



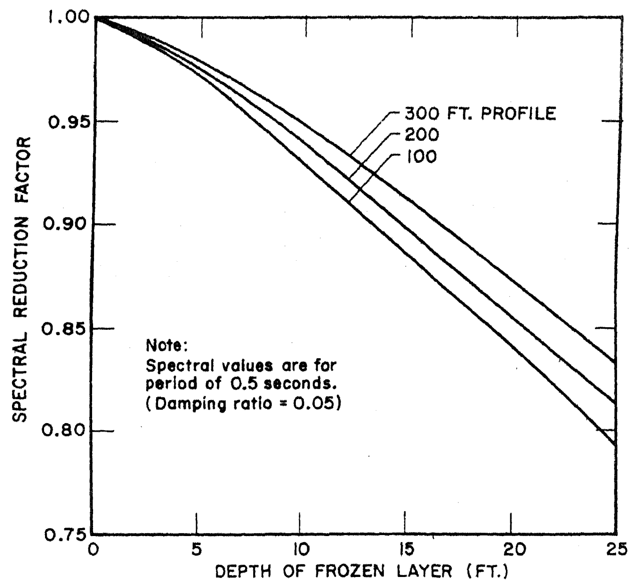
APPROXIMATE DAMPING RATIOS FOR FROZEN SAND

Fig. 2



ATTENUATION EFFECT OF FROZEN LAYER ON PEAK SURFACE ACCELERATION

Fig. 3



ATTENUATION EFFECT OF FROZEN LAYER ON SPECTRAL RESPONSE

Fig. 4