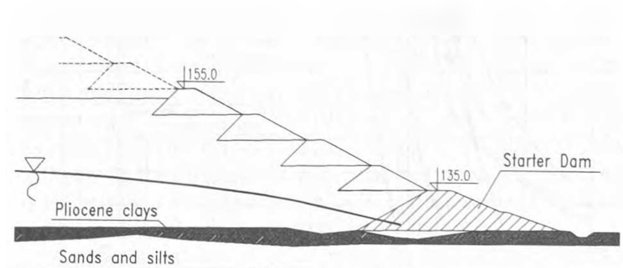
155.0
Starter Dam
135.0
Pliocene clays
Sands and silts

Laboratory test results of the clays have revealed that their drained shear strength parameters are low, with an angle of internal friction slightly exceeding 10° and only few kPa of cohesion. If one accounts for permanent increase in shear stresses on the potential slip surface, it seems that it would not be prudent not to consider possibility of local instability in foundation soils. Such an instability in turn, by sudden change in stress state in the dam body, can convert drainage conditions in tailings material from drained to undrained. As a consequence, high drained shear strength resistance for tailings ($\phi \simeq 35°$) can be changed into undrained residual shear strength, what - accounting for operating stress state - is usually several times lower value.

3 THE TAILINGS MATERIAL

Żelazny Most tailings material is very heterogeneous in granulation and can be classified as sand, fine sand, sandy silt and silt with some clay content. Boundaries for grain size distribution are shown in figure 2. For illustrative purposes, on the grain size distribution plot are also included boundaries for potentially and most liquefiable soils (USNRC 1985) and ranges for tailings slimes with low resistance to liquefaction (Ishihara 1985). It is evident, that Żelazny Most tailings material fits very well into these boundaries and therefore might be considered as a potentially liquefiable.

As it concerns mineralogy of tailings, their material is predominantly quartz, and then dolomite and calcite. There are some bright mica and heavy and nontransparent minerals (metal sulfides and oxides). In minority there are gypsum, potassium, feldspars and mica.

Analysis of shape of the tailings reveals that material coarser than 0.1 mm is in majority subangular and subrounded. There are some singular grains which are rounded. Medium rounded are carbonates grains, while quartz grains are angular and subangular in shape. In the range 0.06 - 0.1 mm dominate subangular grains. Fraction finer than 0.06 mm contains grains which are angular in shape and with visible effects of crushing.

Generally, the deposit of tailings is characterized by a random distribution of thin laminations in the vertical directions and by changes of physical properties in the beach and in the pond area due to the segregation and sedimentation process which intensity is linked to a distance from the crest of the dam. The properties also vary along the dam. In consequence slimes material in a profile is very heterogeneous, stratified with numerous lenses of material consisting only of fines ($\leq$ 0.074 mm). Values of plasticity index of tailings material are in the range 7 -12%.

A comprehensive set of data including numerous classification tests results can be found in the Geoteko Report prepared for foreign experts (1993).

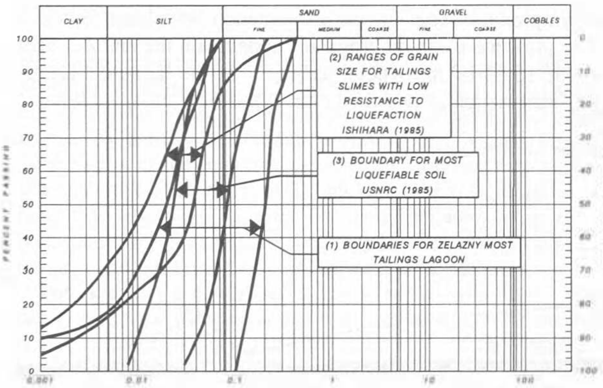

Figure 2. Boundaries of grain size distributions of Żelazny Most tailings material.

4 LIQUEFACTION SUSCEPTIBILITY

Presented boundaries for grain size distributions and low plasticity of the material indicate that tailings predominantly consist of fines and might be susceptible to liquefaction.

If one performs some additional classification tests, separately on sand and fine fraction of the material, it is possible to better characterize its susceptibility to liquefaction by using ternary diagram as described by Carrier (1991). Soil kind in this diagram is represented by SFR - ratio of sand to fines ($\leq$ 0.074 mm) fraction. SFR is very convenient parameter because represents a soil kind as a number. In figure 3 such a ternary diagram constructed on the basis of data collected from Żelazny Most lagoon is presented. As if can be inferred from the diagram majority of tested tailings are prone to liquefaction.

Although, all quoted classification test results clearly indicated that tailings are susceptible to liquefaction, the final analysis of the dam stability should be based on mechanical tests. Standard soundings (SPT, CPTU, DMT) that are performed in Żelazny Most beach material show small penetration resistance, what might indicate potential liquefaction problem, if loading of satisfactory amplitude appears.

However, application of state-of-the-art of in situ methods to estimate liquefaction potential is not in the case of Żelazny Most lagoon straightforward. There are two reasons for that:

- existing relationship between cyclic stress ratios causing liquefaction and SPT, CPT and DMT results refer to bigger cyclic loading than values predicted in Żelazny Most site.
- majority of charts do not account for very high content of fine fraction and considerable heterogeneity of tailings

In order to better understand a nature of liquefaction of slimes, it is advisable to perform laboratory tests with well controlled stress and drainage conditions.

Figure 4 shows some stress strain characteristics from monotonic undrained triaxial tests carried out on tailings material containing 10 % of fines. Specimens were prepared by moist tamping method, saturated and consolidated isotropically to 500

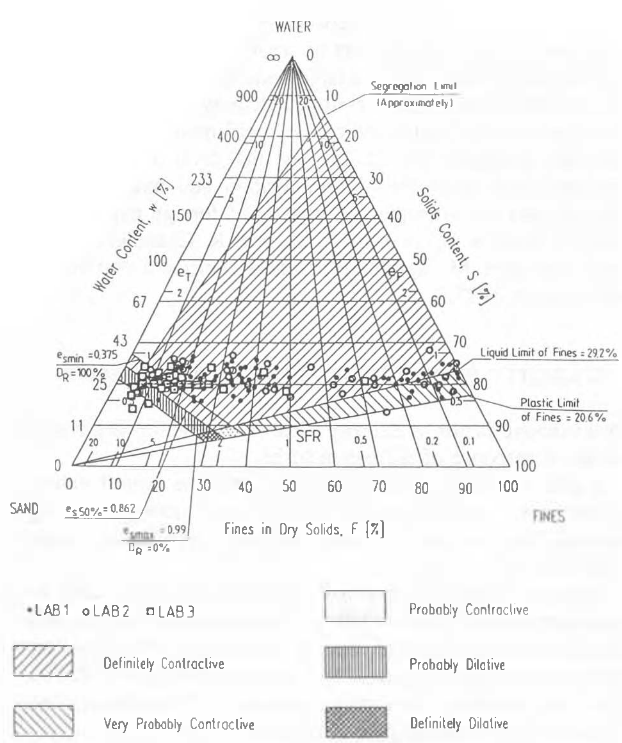

Figure 3. Susceptibility to liquefaction of Żelazny Most slimes based on the ternary diagram.

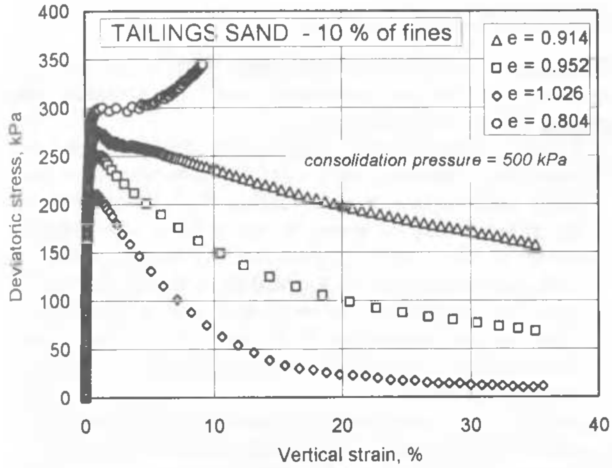

Figure 4. Undrained response of Żelazny Most tailings material from monotonic triaxial tests.

kPa of mean effective stress. At the end of consolidation stage the only parameter which differs specimens was void ratio. Shearing stresses were applied in load controlled conditions. As it can be concluded from the figure, response of tailings and in particular a value of post peak undrained shear strength is strongly dependent on void ratio. In case of three specimens which show definitely contractive behaviour, development of deformations after achievement of instability point lasted only fractions of second. This can serve as an example how refined laboratory techniques are required in order to control properly the test conditions.

5 LIMITATIONS DUE TO SAMPLE DISTURBANCE

The above example clearly indicates that undrained characteristics of sands is very sensitive to even small sample disturbance, and that the only technique of sampling which can preserve intact soil properties is freezing.

Unfortunately, freezing technique can not be applied when sampled soils contains fines, because in this soils freeze/thaw cycle is not recoverable with respect to a structure of soil. This feature makes this technique completely unuseful for tailings material.

In order to show how conventional tube sampling in tailings is representative (with respect to void ratio) for in situ conditions, comparison between such a technique and manual sampling in excavation has been done.

During manual sampling thin wall cylinders were used (diameter to wall thickness ratio greater than 50). Tube sampling have been performed by Mostap Hyson sampler. The results are shown in figure 5 in the form of dry density profiles (5a), and comparison of void ratio change within its boundaries in the wide range of fines content (5b). From fig. 5a it can be contrived that data from sampler are much more scattered and their average dry density with comparison to manual sampling is about 10 % higher. If one presents these results in terms of void ratio referred to its full range change (fig.5b), this 10 % becomes 25 % of error. Furthermore, if one additionally accounts for difference between true in situ void ratio value and value got from manual sampling, the overall error might reach 30-40 % of the parameter full change scale.

The above examples entitle to state that precise determination of void ratio in tailings material by using direct method is not possible. If one additionally realizes how parameters describing soil behavior during liquefaction are sensitive to smallest void ratio change, it will become evident that others approaches to the problem should be looked for.

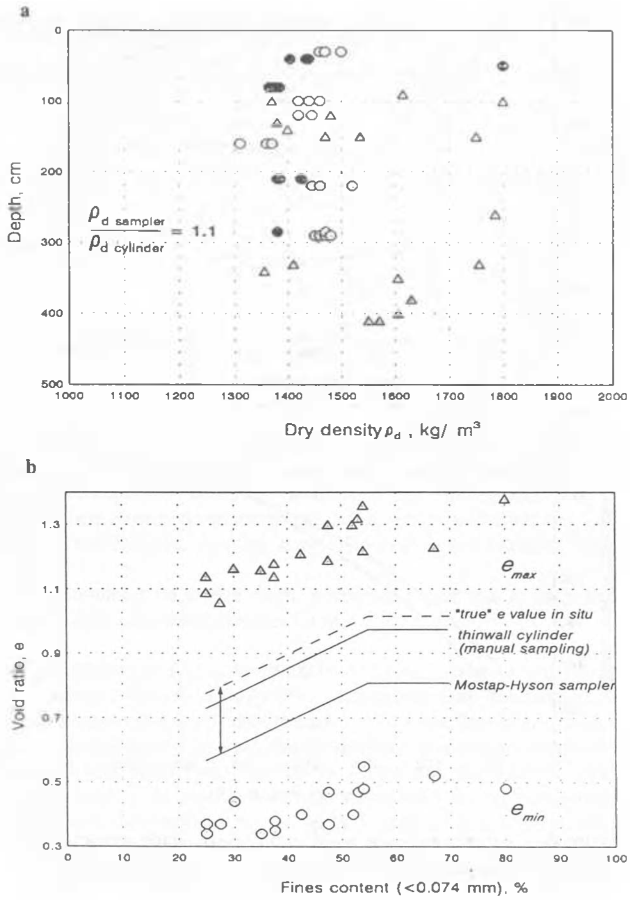

Figure 5. Change in void ratio due to sample disturbance.

6 SUGGESTED METHOD

Taking into consideration the above specified limitations of conventional methods, an alternative (resting on nondestructive technique) approach for evaluation of liquefaction potential of tailings is going to be applied. As indicated by Robertson et al. (1994), Sasitharan et al. (1994) shear wave velocity can be used. The major advantage of the method consists in possibility of measuring shear wave velocity in situ and in a laboratory, thus omitting the problems associated with sampling. In the last years considerable progress has been done in refinement of measuring shear wave velocity in laboratory (Brignoli et al 1995), and in situ (Robertson et al 1992).

Due to the fact that shear wave velocity is propagated through soil skeleton and depends on void ratio and current stresses, state of material prior to destructive loading commencement can be evaluated.

In figure 6, an example of relationship among void ratio, shear wave velocity and state of stress for Zelazny Most tailings material is shown. It is important to note that shear wave velocity reflects very well changes in state of stress and void ratio. In particular, the relationship between void ratio and shear wave velocity is much better than in clean sands, what is manifested by bigger slope of the characteristic e - V_S. More inclined the line, better resolution of the method, because it implies that in slimes contribution of a void ratio change in shear wave velocity increase is greater than it is in clean sands. In the example shown in figure 6, the differece between load and reload characteristics is evident, and therefore anable to distinguish between soil states refering to equal stresses but different void ratio.

Another advantage of shear wave velocity technique consists in the fact that measurement refers to a certain volume of the tailings material, thus the problem with its nonhomogeneity is overcome.

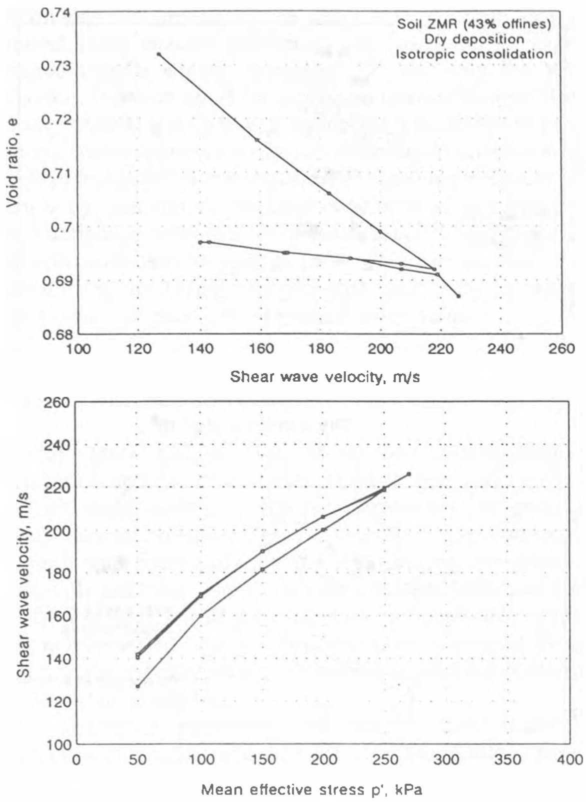

Figure 6. An example of void ratio-shear wave velocity and effective stress relation in Żelazny Most tailings material.

Assuming the above premises the general scheme of the method for evaluation of undrained shear strength during liquefaction via shear wave velocity measurement can be outlined as it is shown in figure 7. The test programme is composed of in situ and laboratory tests. The most important part of it consists in carrying out series of triaxial tests on reconstituted material for evaluation of relationships among shear wave velocity, void ratio and stress state from one side and undrained shear strength during liquefaction from the other. The second branch of the programme covers execution of field tests in order to obtain normalized (with respect to a stress state) value of shear wave velocity. At the phase of analysis the correlation obtained in a laboratory is combined with in situ test results for evaluation of field undrained shear strength during liquefaction. The key issue in this scheme is a quality of laboratory tests.

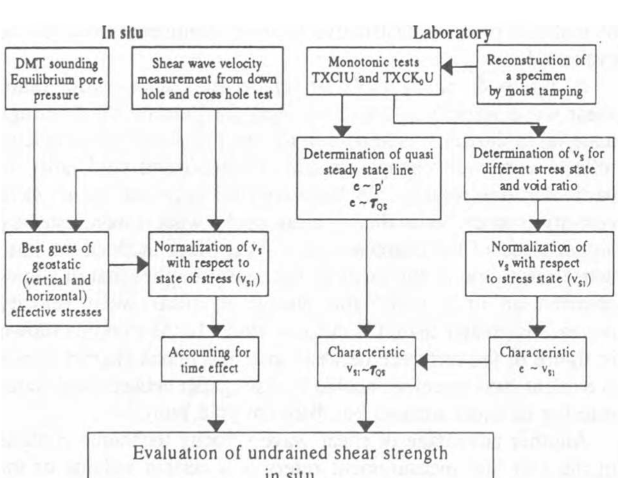

Figure 7. General scheme for evaluation of undrained shear strength during liquefaction by using shear wave velocity.

7 FINAL REMARKS

As a result of the above considerations based on the large number of in situ and laboratory tests the following final remarks can be formulated:

- In Żelazny Most Tailings lagoon case where potential static liquefaction problem might exist, the conventional methods based on earthquake induced loading are not applicable,
- the ternary diagram seems to be a more comprehensive procedure than based on grain size distribution method for preliminary evaluation of potential liquefaction problems
- errors in void ratio determination associated with sampling of slimes can be greater than 30 %, what is unacceptable value with respect to accuracy required in evaluation of undrained response of sands
- use of shear wave velocity in evaluation of liquefaction of slimes is more promising than in case of clean sands, and additionally overcomes problems associated with inherent nonhomogeneity of tailings.

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