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SYNOPSIS

Soil-cement backfills have been analyzed, designed and tested for the Alto Lazio Nuclear Power Plant in Italy. Extensive analyses were performed to evaluate the stability of and stresses in soil-cement foundation backfills. Soil-structure interaction was also analyzed. The minimum required cement content for foundation and general backfills was established and verified by means of laboratory and field tests. Foundation backfills were designed for two major buildings of the plant.

INTRODUCTION

An extensive program of analysis and field testing of the application of soil-cement for construction backfills has been authorized by ENEL, the Italian goverment agency for power, and has been performed by D'Appolonia Consulting Engineers. The work was related to the construction of the Alto Lazio Nuclear Power Plant near Montalto di Castro, Viterbo, Italy.

Excavation for plant construction has taken place to a depth of approximately 15 meters below the original ground surface. A plastic diaphragm wall and deep wells have been used to dewater the excavation (Figure 1). The excavated soil, which is primarily silty sands of volcanic origin, is not suitable for Class A backfills at the site because of particle breakdown during

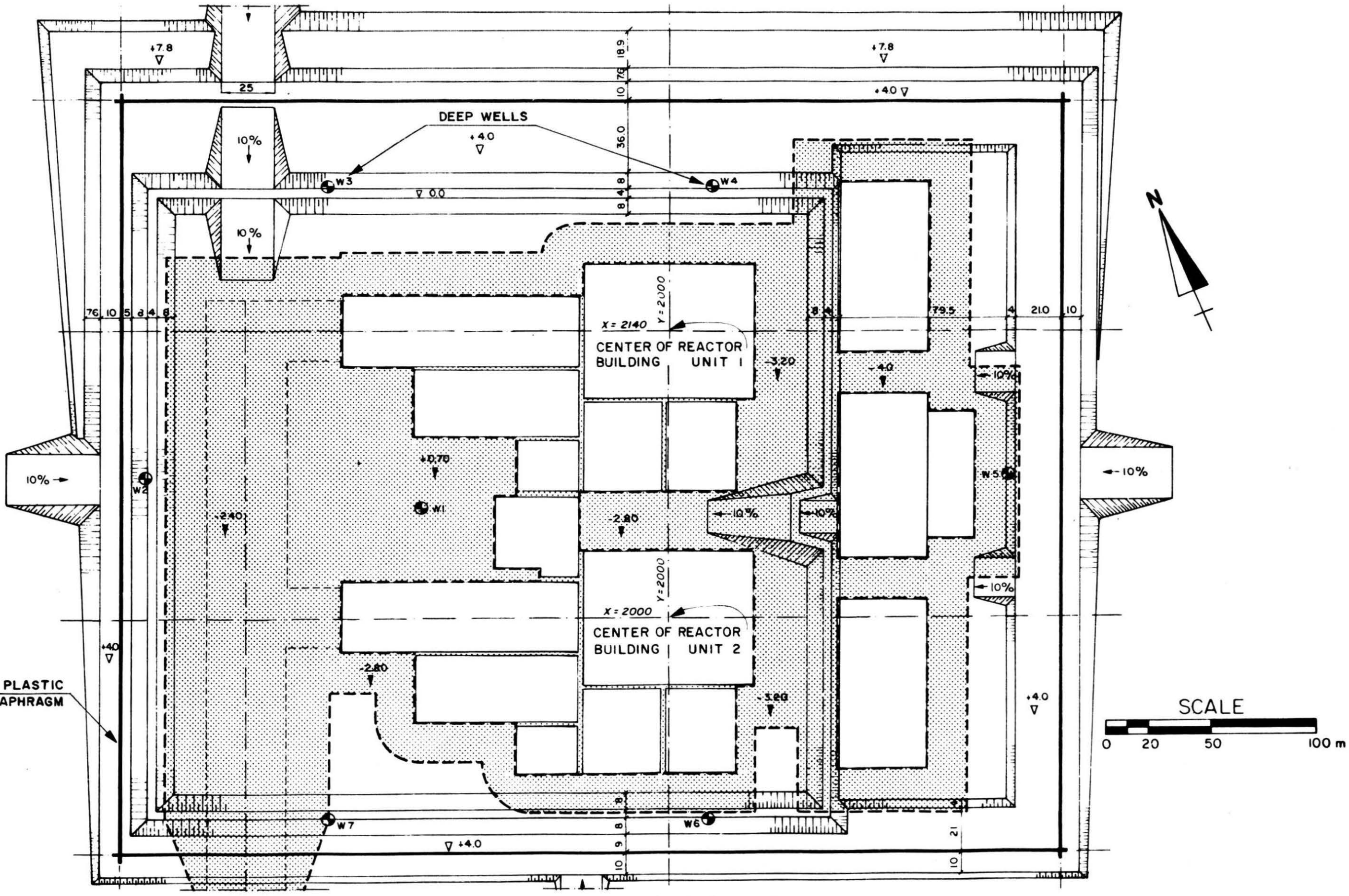

Figure 1. Plant Layout

compaction which makes it impossible to achieve the specified minimum 75 percent relative density (D'Appolonia, 1978). As a consequence, backfilling at the site has proceeded with the use of quarry materials.

The possibility of adding cement to the excavated soil and using the soil-cement mixture for backfills has been investigated. In addition to allowing the use of the excavated soil, soil-cement has the additional potential advantage of allowing construction at multiple levels without the use of retaining structures. The investigation has indicated that soil-cement is suitable for foundation backfills, and the project has been completed to the point that detailed design and placement procedures have been developed. The analyses, laboratory and field testing, and development of placement procedures are presented in this paper.

EVALUATION OF SOIL-CEMENT FOR FOUNDATION BACKFILLS

The use of soil-cement as a foundation material has been analyzed for both the Control Room and Diesel Building at the plant site (Figure 2).

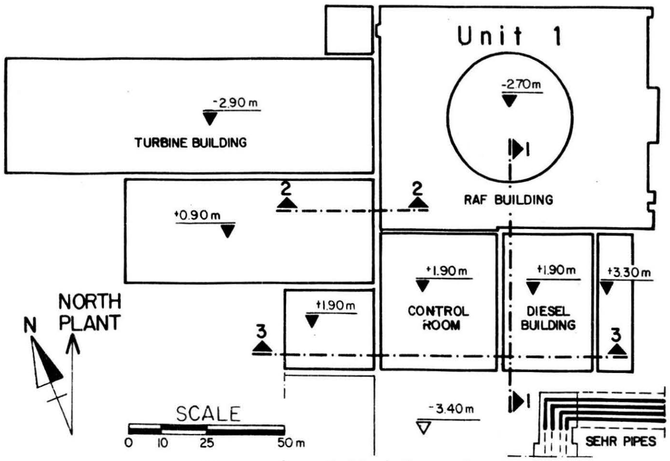

Figure 2. Unit 1 Layout

Analyses were performed to evaluate the quantity of cement to be added to the excavated soil in order to obtain a foundation material suitable for both construction and long-term conditions. Analyses were also conducted to assure that the use of soil-cement backfill would not alter the building behavior determined from previous soil-structure interaction (SSI) analyses (D'Appolonia, 1983a).

Slope Stability Analysis

Potential local and general slope stability failures were analyzed for both static and seismic conditions, as typically illustrated in Figure 3. The Safe Shutdown Earthquake (SSE) was used in the seismic analysis even for construction conditions. The SSE produces a ground acceleration in both the horizontal and vertical directions. The loads transmitted to the underlying foundation materials by the building were obtained from previous building design analyses for SSE conditions.

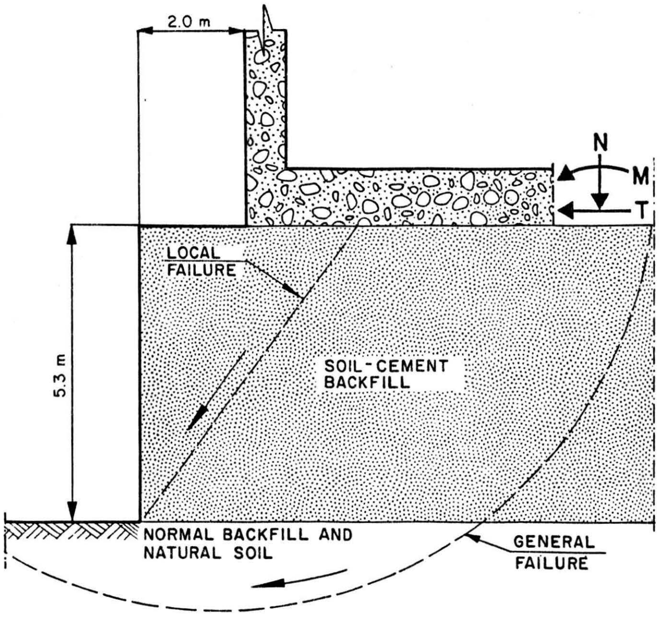

Figure 3. Slope Stability Analysis

Stability analyses were performed using the STABLE2 computer code (Seigel, 1978). A minimum friction angle of 35 degrees was assumed for the soil-cement. The analyses indicated the minimum cohesive strength required for stability was 240 kiloNewtons per square meter for the Control Room and 170 kiloNewtons per square meter for the Diesel Building (Figure 4).

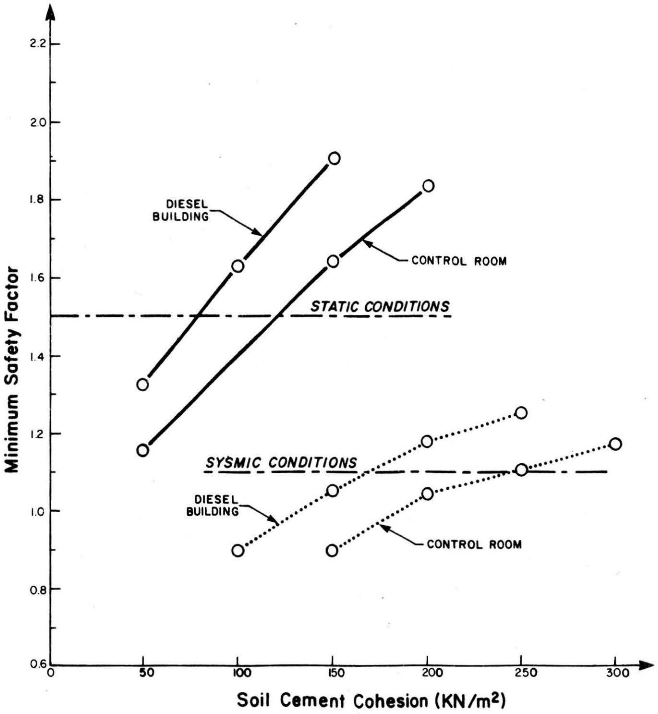

Figure 4. Soil-Cement strength requirements

To account for some strength reduction after placement due to fissuring, a minimum cohesive strength of 500 kiloNewtons per square meter was specified as a design requirement for soil-cement foundation backfill for the two buildings.

Stress Analysis

A stress analysis was performed for a 5.3-meter thick soil-cement slab underlying the Control Room and Diesel Building. SSE conditions were assumed, and the in house finite element computer program DAPSYS (D'Appolonia, 1981) was used to model the soil-cement slab and underlying soils (Figure 5). An elastic modulus ranging between two and 20 times the soil backfill stiffness (400 to 4000 MegaNewtons per square meter) was assumed for the soil-cement slab (Yoder and Witczak, 1975).

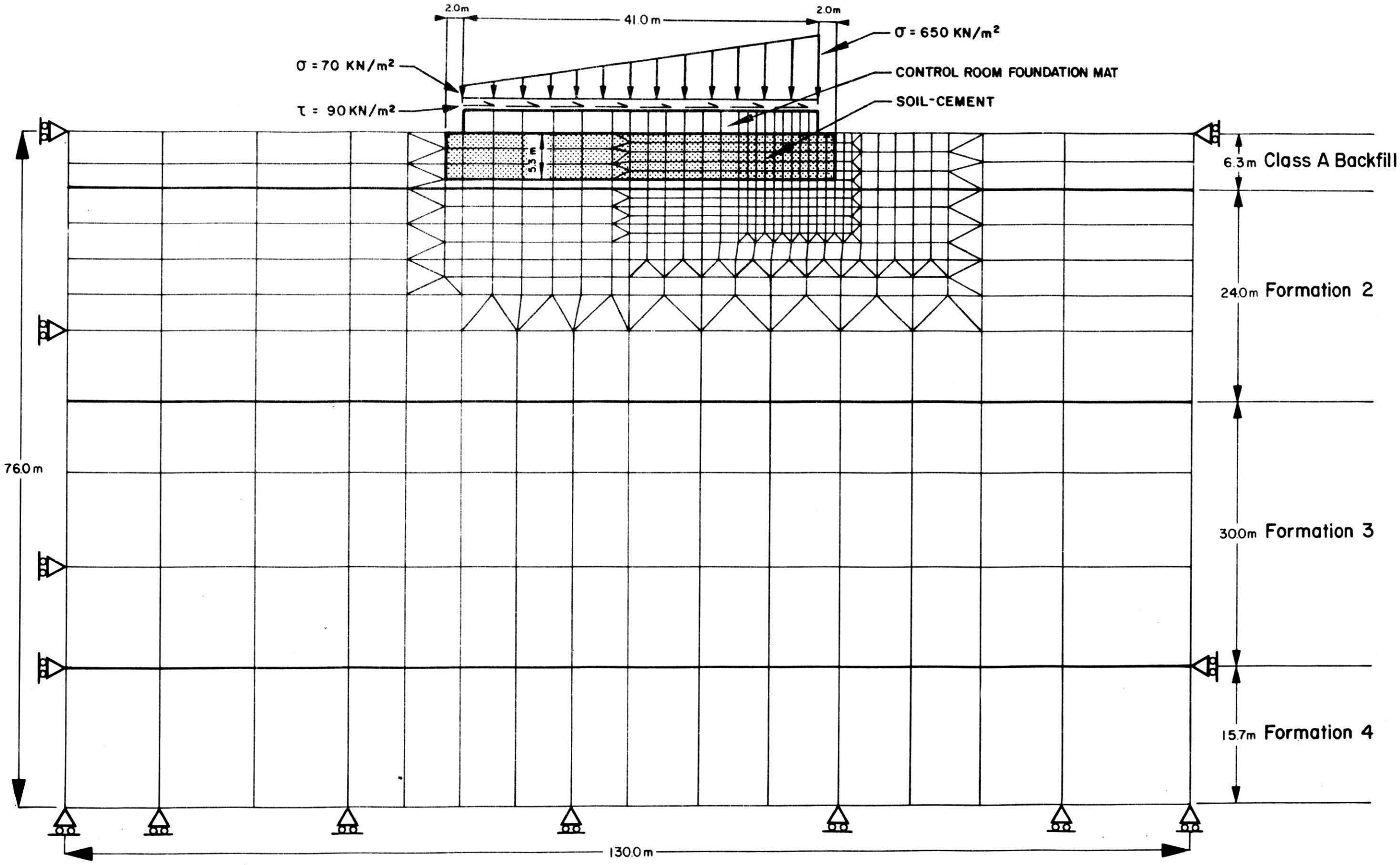

Figure 5. Finite Element Model

The analysis indicated a maximum principal compression stress of 1.44 megaNewtons per square meter and a maximum principal tensile stress of 0.24 megaNewtons per square meter. The soil-cement is assumed to have no tensile strength, and although the tensile stresses could cause some fissuring, this will not affect foundation stability. For a Mohr-Coulomb failure criterion and a friction angle of 35 degrees, a cohesive strength of 230 kiloNewtons per square meter is required to prevent failure in compression. This strength requirement is equivalent to the strength requirement of slope stability.

Soil-Structure Interaction

Because soil-cement backfill is significantly stiffer than normal soil backfill, the SSI analyses previously performed for soil backfill were repeated, incorporating the effect of soil-cement. The following properties were used:

- "Low strength" soil-cement

  Total unit weight: 16 to 19 kiloNewtons per square meter. Shear modulus: 400 megaNewtons per square meter. Poisson's ratio: 0.2

- "High strength" soil cement

  Total unit weight: 16 to 20 kiloNewtons per square meter. Shear Modulus: 4000 megaNewtons per square meter. Poisson's ratio: 0.3.

The natural soil and backfill properties were assumed to have a range of plus or minus 30 percent of the best estimate properties determined from an earlier study (D'Appolonia, 1977). Analyses were performed for a lower bound soil profile of low strength soil-cement overlying natural soil and backfill with lower bound properties and for an upper bound soil profile of high strength soil-cement overlying natural soil and backfill with upper bound properties. A shear modulus reduction with strain was considered for natural soils and backfill, but not for the soil-cement.

Foundation stiffnesses were computed for the vertical, horizontal and rocking modes using the D'Appolonia program WGTMOD, which is based on the lumped parameter approach described by Richart, Hall and Woods (1970) and the method of accounting for layering presented by Christiano et al. (1974). A correction factor was used to account for the presence of the soil-cement. The correction factor was obtained from two-dimensional finite element analyses of the soil profile with and without the soil-cement. A correction for foundation embedment was also employed and was based on a method presented by Johnson et al. (1975).

The dynamic response of a building on the model soil profiles was accomplished by a response spectrum analysis using USNRC Regulatory Guide 1.60 spectra scaled to 0.18 g. The D'Appolonia computer code DAPSYS was used. The structural model of the Control Room is shown in Figure 6.

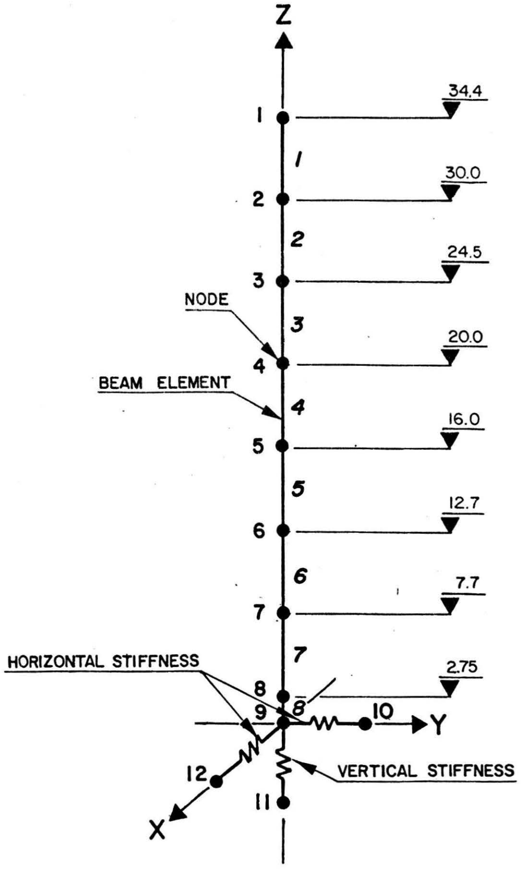

Figure 6. Soil-Structure Interaction Model

The influence of the soil-cement on total foundation stiffness is a function of the strength (stiffness) of the soil-cement and the direction of motion. The influence of the soil-cement is very significant for horizontal motion, the stiffness increase ranges from 45 to 58 percent for low and high strength soil-cement, respectively. For vertical motion the increases are 7 and 14 percent, while for rocking the respective increases are 17 and 33 percent.

In general the lower foundation stiffnesses (spring constants) result in higher forces transmitted between soil and structure. Thus the forces transmitted by the Control Room to the soil-cement backfill generally are less than the corresponding forces for a building on natural soil backfill. Natural frequencies obtained for soil-cement backfill are similar to those obtained for natural soil backfill.

EVALUATION OF SOIL-CEMENT FOR GENERAL BACKFILL

Soil-cement was considered for use as general backfill to eliminate the need for importing quarry materials and to utilize previously unsuitable soils from the plant excavation (D'Appolonia, 1983b). A number of factors were considered in order to establish design parameters for soil-cement used as general backfill. These factors are:

- bearing capacity and settlement,
- liquefaction,
- lateral soil pressures,
- ease of excavation, and
- soil structure interaction (minor buildings only).

Bearing capacity considerations resulted in a minimum friction angle of 35 degrees, while settlement considerations require an elastic Young's modulus of at least 22 megaNewtons per square meter. To preclude the possibility of backfill liquefaction, a minimum cohesive strength of 50 kiloNewtons per square meter is required. Lateral earth pressure considerations impose no additional requirements than the preceding (D'Appolonia, 1983c), and a maximum value of Young's modulus of 2000 megaNewtons per square meter is required for ease of excavation. Soil-structure interaction problems must be considered by evaluating the specific foundation sizes and loadings.

LABORATORY AND FIELD TESTS

A program of laboratory and field testing was carried out in order to establish soil-cement composition and placement techniques that would satisfy the requirements determined from the analyses; these requirements are summarized in Table 1.

TABLE I: LIMIT DESIGN PROPERTIES OF SOIL-CEMENT

DESIGN ASPECTS	DESIGN PARAMETERS	FOUNDATION BACKFILLS (1)	GENERAL BACKFILLS
SLOPE STABILITY	COHESION AND FRICTION ANGLE	500 kN/m^2 and 35°	-
STRESS LIMITS	COHESION AND FRICTION ANGLE	500 kN/m^2 and 35°	-
BEARING CAPACITY	FRICTION ANGLE	-	35°
SETTLEMENTS	ELASTIC MODULUS	-	22 MN/m^2
LIQUEFACTION	COHESION	-	50 kN/m^2
EARTH PRESSURE	FRICTION ANGLE	-	35°
EXCAVATION EASE	ELASTIC MODULUS	-	2000 MN/m^2

Note: (1) Control Room Foundation

Laboratory Testing for Foundation Backfills

If a Mohr-Coulomb failure criterion is assumed for soil-cement, the unconfined compressive strength that corresponds to an effective cohesive strength of 500 kiloNewtons per square meter and a friction angle of 35 degrees is 2000 kiloNewtons per square meter (Hendron, 1968). Unconfined compressive strength was defined as the design strength criterion for soil-cement, and laboratory testing of various soil-cement mixes was performed. Ultrasonic testing was also performed to determine the dynamic shear modulus. The laboratory tests were perfomed on samples with cement contents of five, eight and 11 percent at compaction densities of 90 and 100 percent of the maximum ASTM D 558 dry density. Curing times of seven and 28 days were used. The resulting unconfined compressive strengths and values of dynamic shear modulus (low-strain) are presented in Figure 7.

As can be seen from Figure 7, the unconfined compressive strength and dynamic shear modulus of soil-cement increase significantly with increasing cement content and relative density and also with the increase in curing time from one to four weeks. From Figure 7 it is concluded that eight percent cement content and a compaction density of 95 percent (ASTM D 558) will provide the minimum unconfined compressive strength (2000 kiloNewtons per square meter) required for building foundations.

From Figure 7 it can be seen also that the dynamic shear modulus falls in the range of 400 to 4000 megaNewtons per square meter, which was assumed in the analyses. Thus a cement content in the range of five to 11 percent will pose no problems for building foundations.

Laboratory Testing for General Backfills

Laboratory testing was performed on soil-cement samples with cement content ranging from two to four percent. The samples were compacted to 95 percent of maximum ASTM D 558 dry density and were cured from seven to 28 days.

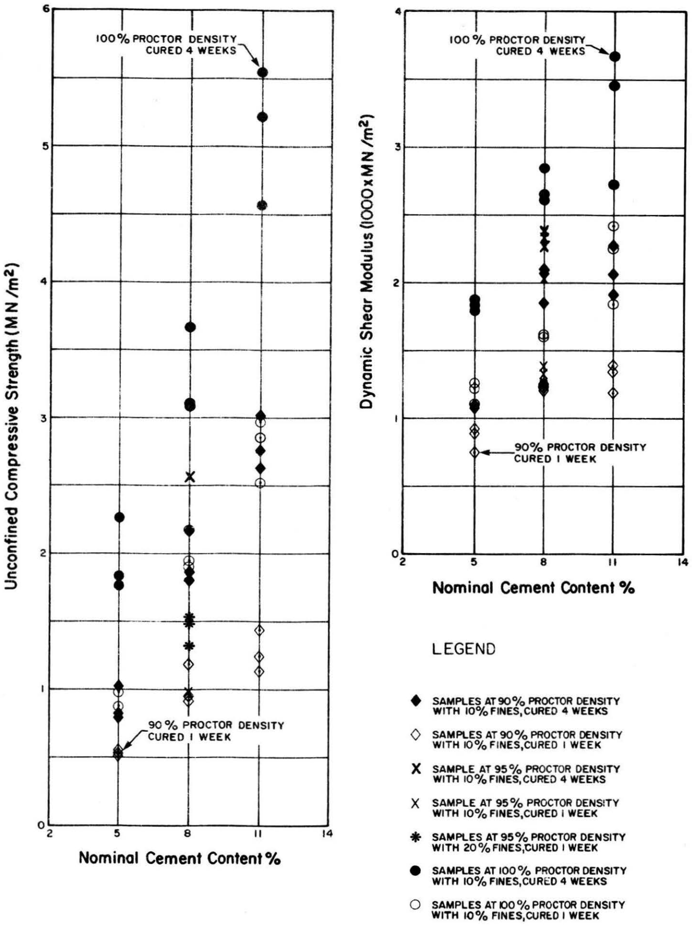

Figure 7. Laboratory Soil Cement Properties Vs. Cement Content

Soil-cement with cement content in the two to four percent range is a much more soil-like material than when the cement content is in the five to 11 percent range considered above. Accordingly, tests were directed toward the determination of Mohr-Coulomb effective stress parameters and static stress-strain parameters, as is the usual practice with soils. Therefore unconsolidated-undrained and isotropically consolidate-undrained triaxial tests were performed on the soil-cement samples. Strength and modulus values determined from these tests are provided in Table 2.

TABLE 2: LOWER BOUND LABORATORY PROPERTIES SOIL-CEMENT FOR GENERAL BACKFILL

NOMINAL CEMENT /WATER CONTENT (%)	EFFECTIVE FRICTION ANGLE (degrees)	EFFECTIVE COHESION INTERCEPT (kN/m^2)	ELASTIC MODULUS AT 10 kN/m^2 CONFINING PRESSURE (1)	ELASTIC MODULUS AT 80 kN/m^2 CONFINING PRESSURE (1)
2/24.0	35	10	10000	20000
4/24.0	36	170	(2)	(3) 100000

NOTES:

1) Young's secant modulus at one percent axial strain.

2) Insufficient data to estimate this value.

3) Estimated solely on the basis of UU test results.

It is concluded from the data that a soil-cement mix with four percent content compacted to 95 percent of maximum dry density (ASTM D 558) satisfies the design criteria of an angle of friction greater than 35 degrees, effective cohesive strength greater than 50 kiloNewtons per square meter, and elastic modulus in the range of 22 to 2000 megaNewtons per square meter. Acceptability with regard to soil-structure interaction must be analyzed on a case by case basis.

Field Testing Program

Two trial backfills (Trial A and Trial B) were constructed in the field, as shown schematically in Figure 8. A vertical backfill face after removal of temporary supports is shown pictorially in Figure 9.

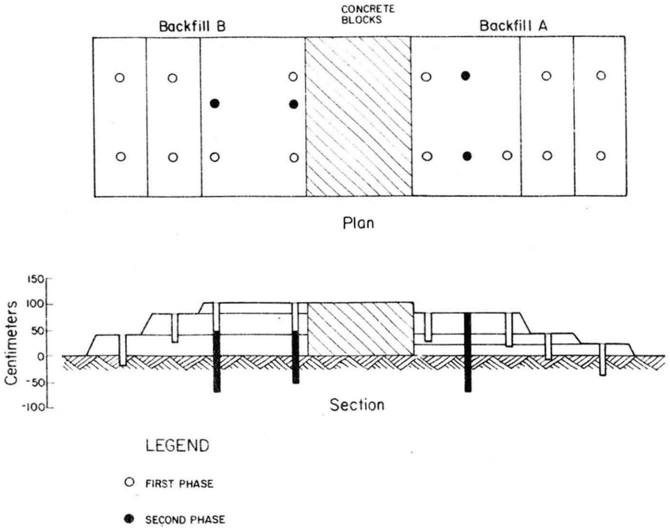

Figure 8. Trial Backfill

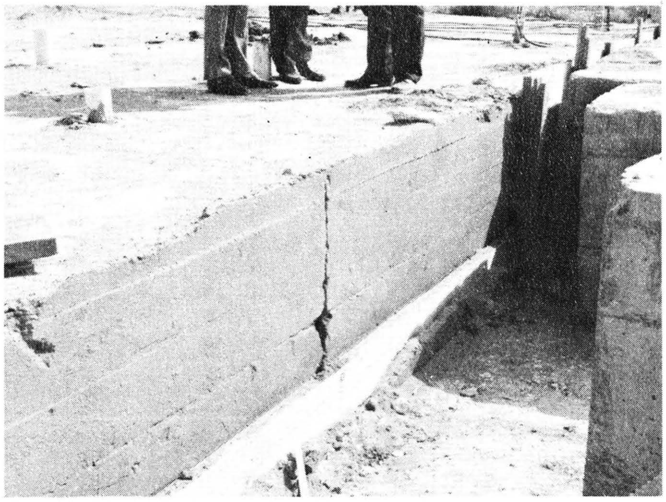

Figure 9. Vertical Backfill Face

An eight-percent cement content was used for both backfills. Trial A was placed without adding water to the mix, but the backfill surface was kept wet after placement and compaction. In Trial B, water was added after placement and during compaction of the individual lifts.

The soil-cement was mixed with equipment normally used in construction. Both a static and a dynamic roller were tested during compaction with the number of passes ranging from three to six for the static roller and from five to 10 for the dynamic roller. Lift thicknesses of 20 and 40 centimeters were used.

Density and moisture content tests were performed immediately after backfill placement and were repeated after six to seven days. The measured dry density values were plotted as a function of layer thickness, roller type and number of passes in Figures 10 (a, b, c). The variations of dry density and water content with time are shown in Figures 11 (a, b).

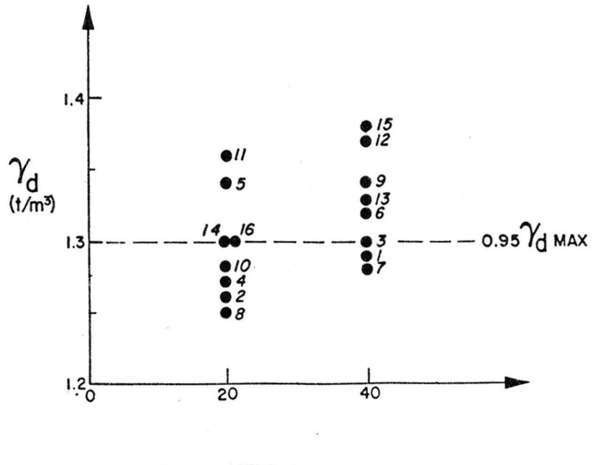

Figure 10a

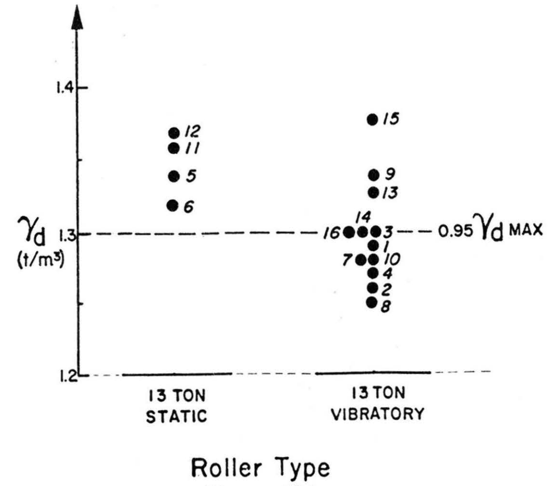

Figure 10b

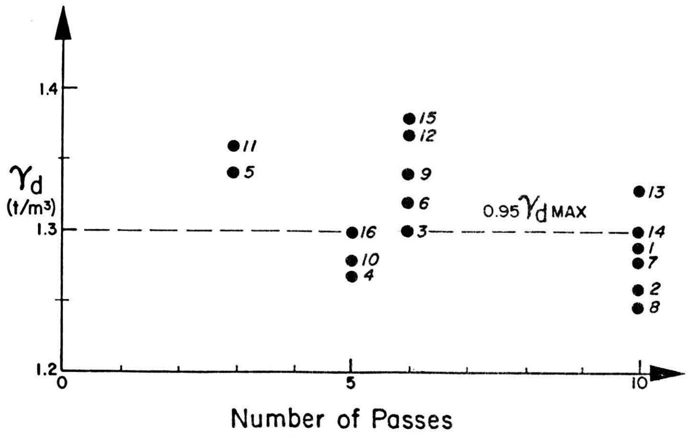

Figure 10c

Figure 10. Dry density as a Function of Placement Conditions

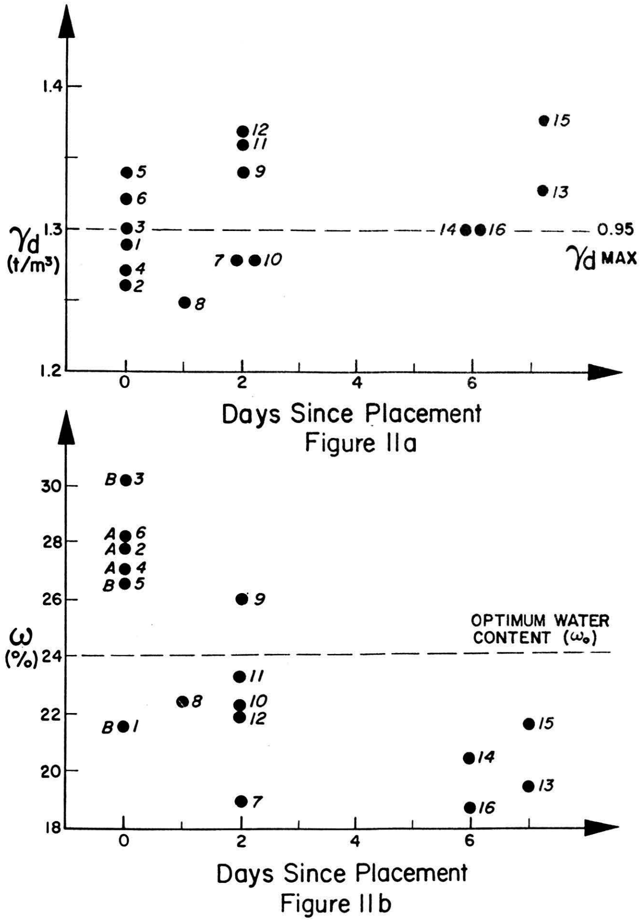

Figure 11a

Figure 11b

Figure 11. Dry Density and Water Content as a Function of Curing Time

From the data it can be concluded:

- A static roller provides better compaction densities
- A static roller requires fewer passes than a dynamic roller
- A lift thickness of 40 centimeters results in higher densities than a lift thickness of 20 centimeters.

The optimum placement and compaction procedure for soil-cement with an eight-percent cement content consisted of 40-centimeter lifts compacted with six passes of a static 13-ton roller.

Water contents in Trial A exhibited less scatter than in Trial B. This was probably the reason for the observed better curing in Trial A, as indicated by the variation with time of shear wave velocities from cross-hole tests.

Cement content tests indicated considerable non uniformity in the trial backfills. As a result, subsequent mixing tests were performed using a concrete mixer truck, but no substantial improvement in cement content uniformity was achieved. On the basis of these results, traveling-type mixing machines are recommended for future applications, subject to test verification.

Shear wave velocities (Vs) and compression wave velocities (Vp) in the trial backfills were measured by ISMES (1983) using the cross-hole method. The cross-hole tests were carried out in two phases, one week and four weeks after backfill placement, to determine the effect of curing time. The test locations are indicated in Figure 9. Measured values of Vs and Vp are provided in Figures 12 and 13 for Trial A and Trial B, respectively. After four weeks, Vs generally ranged from 500 to 750 meters per second and Vp from 1200 to 1600 meters per second. The shear wave velocity was found to have increased significantly more in Trial A than in Trial B, and it is concluded that this is the result of more uniform water content in Trial A.

The dynamic shear modulus (low-strain) values of Trials A and B after four weeks were in the approximate range of 400 to 900 megaNewtons per square meter. These values fall in range considered earlier for analysis. Soil-cement backfills with a more uniform cement content should yield dynamic shear moduli somewhat larger than the values measured in the trial backfills.

DETAILED DESIGN

A detailed design was developed for foundation backfill for two major buildings at the Alto Lazio Nuclear Power Plant. The design was developed for foundation backfills for the Radwaste and Offgas Buildings because of the declining availability of quarry material and because of geometric restrictions in construction which make steep slopes attractive. A cement content of eight percent and a minimum density of 95 percent of ASTM D 558 were specified for a proposed 2.4-meter thick soil-cement slab.

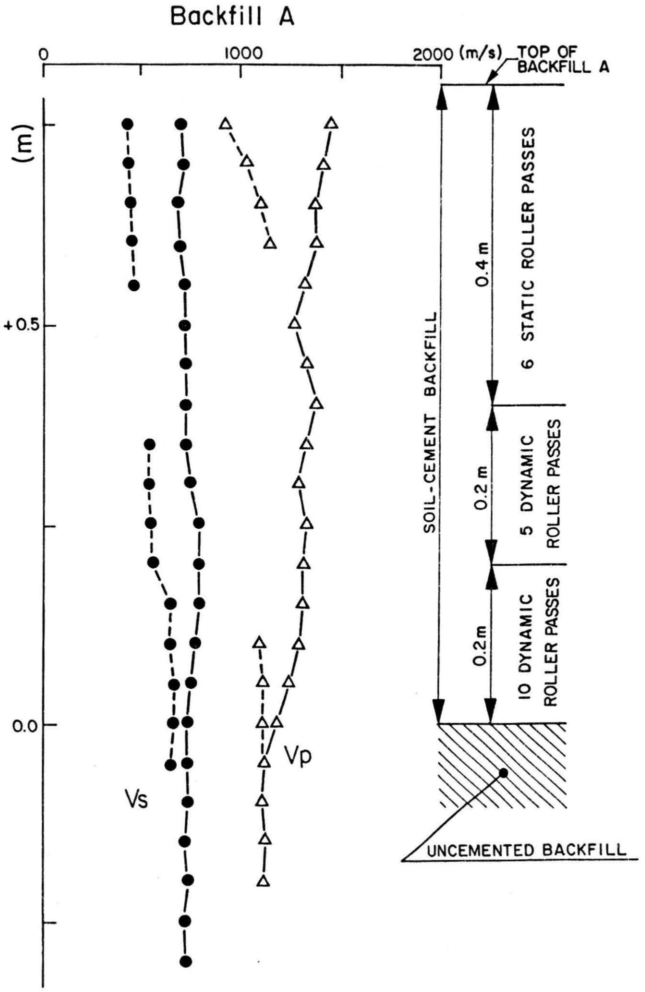

Figure 12. Cross-Hole Test, S-Wave and P-Wave velocities in Backfill A

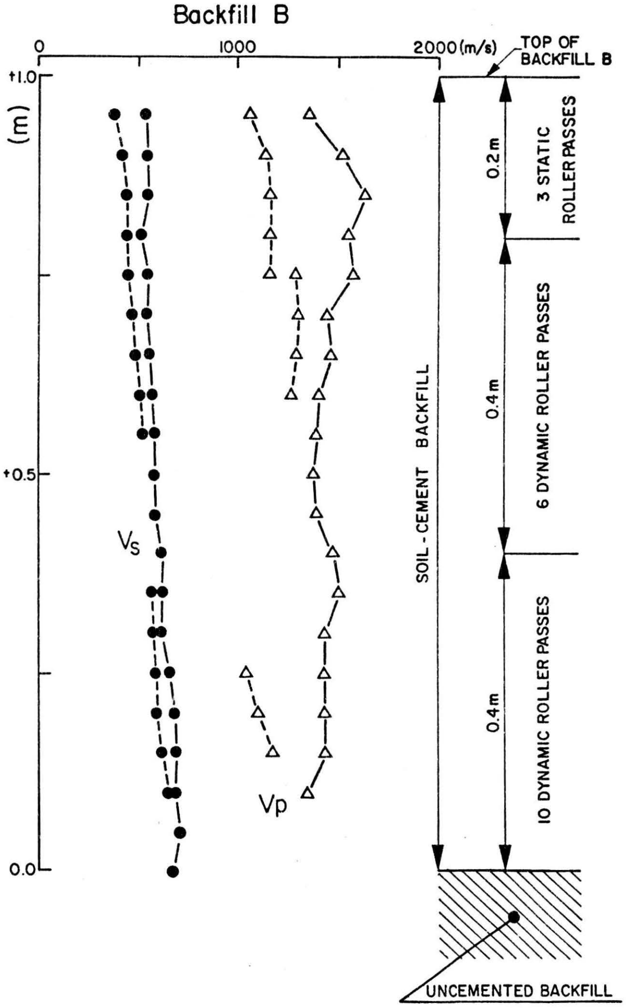

Figure 13. Cross-Hole Test, S-Wave and P-Wave velocities in Backfill B

Slope stability for the temporary and permanent configuration of backfill was analyzed for static and dynamic conditions using the STABL2 computer program. The minimum computed factors of safety for static and dynamic conditions were 2.1 and 1.1, respectively, indicating that slope stability is not a problem during or following construction.

Stress analyses of the proposed 2.4-meter thick soil-cement slab were made to verify that stresses are within allowable limits. The analyses included an assessment of stress concentrations along the edges of the building foundations, computations of the flexibility of the soil-cement slab relative to the underlying soils, and an analysis of bending stresses in the soil-cement for a three-layer system consisting of soil-cement, quarry material backfill and natural soil.

The analysis of stress concentrations along the edges of the building foundations was performed with the assumption that the building foundations were rigid and considering the maximum dynamic loadings. For a rigid foundation on an elastic half space and plane-strain conditions, the most conservative combination of calculated stresses in the soil-cement corresponds to an unconfined compressive strength of less than one megaNewton per square meter.

The analysis of flexibility of the soil-cement slab indicated that it was very flexible and would not act as a structural member and pick up stresses. The specific analysis of the three-layer system consisting of soil-cement, quarry material backfill, and natural soils indicated no tensile stresses. The stress analyses described were consistent with earlier analyses including finite element analyses.

An examination of soil-structure interaction indicated no variations with respect to previous analyses for normal soil backfill.

Technical specifications were provided, indicating an allowable range of variation of cement content of plus or minus two percent from the nominal value of eight percent. Because satisfactory control of cement content was not achieved during the field test program, the use of a traveling-type mixing machine was recommended.

To verify that the recommended mixing equipment was adequate, a test program as part of the initial placement of backfill was recommended.

CONCLUSIONS

Soil-cement backfills have been analyzed, designed and tested for the Alto Lazio Nuclear Power Plant in Italy. For this site soil-cement has the particular advantage that it allows the use of soils excavated for plant construction which were not suitable for Class A backfills because of particle breakdown during compaction. Soil-cement has the additional advantage that vertical faces can be left without lateral support, which facilitates construction in the geometrically restricted areas that exist on the site.

Extensive analyses were performed to evaluate the stability of and stresses in soil-cement foundation backfills under seismic conditions for the plant Control Room and Diesel Building. Additional analyses were performed to verify that soil-cement would not affect soil-structure interaction behavior.

Limit soil-cement properties were established relative to shear strength and dynamic shear modulus, and laboratory and field testing were performed to determine the placement and mixture procedures that would provide the desired properties. Soil-cement with an eight percent cement content compacted to 95 percent of ASTM D 558 maximum dry density was found to be suitable for foundation backfills. Soil cement with a four percent content compacted to 95 percent of ASTM D 558 maximum dry density is suitable for general backfills. The properties of the soil-cement as determined from field and laboratory testing fell within the ranges assumed in the analyses.

The use of soil-cement for foundation or general backfills has been verified for the soils and design conditions associated with the Alto Lazio Nuclear Power Plant. Based on the results of analyses and field and laboratory testing described herein, foundation backfills were designed for two buildings at the plant site.

ACKNOWLEDGEMENTS

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