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REDDY D.V. et BOBBY W.
Memorial University of Newfoundland, Canada

MAHRENHOLTZ O.
Technische Universität Hannover, R.F.A.

Ultimate load behaviour of "cut-and-cover" underground nuclear reactor containments with reinforced earth backfill

Le comportement en charge limite des enceintes des réacteurs nucléaires souterrains avec un comblement de terre armée

On considère une enceinte du type "trancher et couvrir" du béton précontraint, en forme de fer de cheval, dans un milieu argileux avec un comblement de terre armée, et pour ça, on examine la réponse non-linéaire aussi statique que dynamique à la pressurisation interne par suite d'un accident causé par la perte du fluide refroidissant. Le travail continue des recherches préliminaires qui indiquent les effets favorables d'un comblement de terre armée et l'efficacité de l'enceinte souterraine, en forme de fer de cheval, pour des chargements statiques, explosives et sismiques. Des conditions de chargement en forme de précontraitement soutenu et de pression interne statique/dynamique sont considerées. Le critérium elastique Drucker-Prager est employé pour le béton et pour le sol; on rend compte du renforcement de la terre par la raideur qui est barbouillée sur les elements de sol associés. L'effet du précontraitement est simulé par un pression normal équivalent vers l'intérieur situé à la ligne centrale approximative de l'enceinte. Le pouls employé pour l'analyse dynamique est similaire an pouls dû à un accident de perte de fluide refroidissant. On met à exécution l'analyse des éléments finis axisymétriques pour diverses combinaisons des milieux (béton/terre armée/argile).

INTRODUCTION

Nonlinear structure-medium interaction is studied for the static and dynamic response of a 'cut-and-cover' type of nuclear reactor containment to pressurization following an accident, such as a loss-of-coolant accident (LOCA). Earlier work had indicated favourable effects of the reinforced earth backfill in 'cut-and-cover' type underground containments subjected to seismic loadings. The objective is to study the ultimate load behaviour under internal pressure for such a backfill.

REVIEW OF LITERATURE

The concept of underground siting has been extensively studied in view of its inherent, structural, biological, and ecological benefits. Using finite element analysis, Reddy, Moselhi, and Sheha (1) presented parametric studies of the dynamic response of underground nuclear reactor containments subjected to horizontally applied blast excitation. Four principal underground concepts: cut-and-cover in rock or soil, unlined cavity in rock, lined cavity in rock or soil, and lined cavity in rock or soil with an annular filling of soft material - were studied with respect to shape, backfill material, cavity wall reinforcement, and passive and active rock bolting. El-Tahan and Reddy (2) studied the seismic response of the 'cut-and-cover' type underground containment using the computer codes LUSH (plane-strain finite element) and SHAKE (one-dimensional wave propagation). Parametric studies were carried out for: 1) containment shape (high horseshoe, flat horseshoe, and semi-circular roof-vertical walls), 2) relative stiffness of the containment and the medium, 3) depth of burial of the containment (shallow intermediate and deep embedments), 4) relative stiffness of the medium and backfill material (original soil, loose sand, stabilised sand, reinforced earth), 5) thickness of the backfill jackets (10ft and 70 ft), 6) isolation of the containment using energy absorbing jackets around the containment (polyurethane foam and foamed concrete), and 7) type of the surrounding medium (sand and rock). The effectiveness of high horseshoe shape, the cushioning effect of a low stiffness material around the containment, and the reduction in the containment stresses of about 20% by a reinforced earth jacket are among the findings of the study. The static and dynamic nonlinear response to internal pressurization, due to a loss-of-coolant type accident, of a 'cut-and-cover' prestressed concrete horseshoe-shaped containment in a clay medium, with and without a stiffening (concrete/foamed concrete) jacket, was investigated by Mahrenholtz, Reddy, and Ramamurti (3). Axisymmetric finite element analysis was carried out for sustained prestress and sustained prestress and static/dynamic internal pressure loading conditions. The results indicate considerable increase in structural integrity due to embedment.

A number of significant analytical and experimental investigations of elasto-plastic behaviour of above-ground reinforced and prestressed concrete pressure vessels have been presented in Refs. 4 and 5. Various material models for concrete and soil have been developed to represent cracking and nonlinear behaviour. The pressure vessels were modelled by finite elements with three-dimensional and axisymmetric solid finite elements to model the concrete and thin shell, and axisymmetric membrane and bar elements for the layers of steel. Cracking in tension of concrete and elasto-plastic behaviour of concrete in compression and steel in tension have been considered. Argyris, Faust, and Willam (6) described a finite element approach to fracture for the limit load analysis of thick-walled concrete structures. The Mohr-Coulomb criterion was augmented by tension cut-off to describe mechanisms of failure. A refined five-parameter model for the material response, in failure and post-failure regimes, has been presented by Argyris, Faust, Szimmat, Warnke, and Willam (7), which can be particularized to a number of simple failure conditions, Von Mises, Drucker-Prager, etc. Geistefeldt (8) proposed a three-element model with stiffness contribution from the cracked and uncracked portions, including shear in cracks. The percentage contributions of the components depend on the state of stress. Smith, Cook, and Anderson (9) presented constitutive models for reinforced concrete. An orthotropic stress-strain relationship was assumed for short-term loads, and a viscoelastic creep model for long-term loads.

The soil has been modelled (4,5) by frequency-independent and frequency-dependent springs and dashpots, and by finite element representations. The foundation was treated as i) a homogeneous elastic or viscoelastic half-space, ii) a homogeneous viscoelastic layer overlying a rigid medium, and iii) a homogeneous viscoelastic layer overlying a homogeneous viscoelastic halfspace. In finite element analysis, the semi-infinite soil medium is modelled by a sufficiently large domain, such that the effects at the boundary elements are negligible. To minimize computation, smaller domains with energy absorbing boundary conditions have been used. Simple exact solutions representing decay at infinity, used to supplement numerical computation, have been reported by Zienkiewicz (10), and Gudehus (11).

Reinforced earth retaining walls have been gaining importance since their promotion by Vidal (12). Harrison and Gerrard (13) modelled reinforced earth as alternating layers of soft elastic material and flexible unstretchable sheets. Romstad, Herrmann, and Shen (14) presented a 'unit cell concept' in which the reinforcement effect is averaged over the associated soil resulting in orthotropic properties for the soil. Plane strain finite element formulation was used to study a reinforced earth wall. Herrmann and Yassin (15) presented a similar finite element formulation in which the element stiffness contributions of the soil, reinforcement, and springs representing the bond between them are directly combined. An alternative approach, in which the reinforcing strips were discretely modelled, was also presented. A reinforced earth wall was analysed by the two approaches and the results agree well. Al-Hussaini and Johnson (16) presented a two-dimensional finite element formulation for the analysis of reinforced earth wall. Interface elements were used between the reinforcement and soil, and between soil layers. The results were compared with a field test. Naylor (17) used a two-dimensional plane strain finite element formulation to analyse a reinforced earth wall. The stiffness of the soil and reinforcement were combined. An additional degree of freedom was introduced to represent the slip between the reinforcement and soil. Reinforced earth was used as backfill for 'cut-and-cover' type underground containment in Ref. 2. The reinforcement was modelled by rigid elements assuming predominant shear deformation under seismic loading.

ANALYSIS

The structure analysed is a prestressed concrete horseshoe-shaped containment in a clay medium with reinforced earth backfill. The choice of the high horseshoe shape and reinforced earth backfill were based on studies of response to earthquake excitation carried out in Ref. 2. Comparison of stresses in the containment and soil, acceleration response, and excavation volume for three concepts of the same area - i) semi-circular roof with vertical walls, ii) a high horseshoe with dome rise-to-span ratio of 1/2, and iii) flat horseshoe with rise-to-span ratio of 1/4 - indicated the high horsehsoe to be the best. A reduction in the containment stresses of about 20% was achieved using reinforced earth backfill. The finite element discretisation for the axisymmetric analysis using the programme NONSAP (18) is shown in Fig. 1. The different media patterns analysed, reinforced earth/foamed concrete/clay (Fig. 1), are listed in Table 1. The foamed concrete jacket is considered in view of its advantages as an isolation material (1,2).

The loading conditions considered are i) sustained prestress only, and ii) sustained prestress and internal pressure. The effect of prestressing is simulated by an equivalent inward normal pressure at the approximate centre-line of the containment. Prestress is assumed to be applied after backfilling. Both static and dynamic loading conditions are considered. The pulse used for dynamic analysis is similar to that due to a loss of coolant accident. The static effect of the prestressing force is taken into account by assuming it to be uniform, and considering the altered geometry due to prestress-induced initial displacements.

The Drucker-Prager yield condition, used for the plastic modelling of the prestressed concrete and media, is given by

$$3\alpha'\sigma_m + \bar{\sigma} - k \leq 0 \qquad \ldots 1$$

where

$$\alpha' = \frac{2 \sin \phi}{\sqrt{3}(3-\sin \phi)} \quad \text{and} \quad k = \frac{6c \cos \phi}{\sqrt{3}(3-\sin \phi)},$$

in which σ_m = mean stress, $\bar{\sigma}$ = square root of the second invariant of the stress deviation, c = cohesion, and ϕ = angle of friction. For concrete, the values of c and ϕ, which define the yield surface, are found from its compressive, σ_{cu}, and tensile, σ_t, strengths.

$$\sigma_{cu} = \frac{2c \cos \phi}{1-\sin \phi} \quad \text{and} \quad \sigma_t = \frac{6c \cos \phi}{3+\sin \phi} \qquad \ldots 2$$

Reinforced earth is considered as a composite material, and the stiffnesses of the components, loose sand and reinforcement, are directly combined together. Loose sand with a small cohesion value is assumed to be governed by the above yield criterion, Eqn. 1, and the reinforcement associated with a soil element is assumed to behave like a linear orthotropic material; the stress-strain matrix, $\hat{c}$, for the axisymmetric case is given by

$$\hat{c}^{-1} = \begin{bmatrix} 1/E_a & -\nu_{ab}/E_b & 0 & -\nu_{ac}/E_c \\ -\nu_{ba}/E_a & 1/E_b & 0 & -\nu bc/E_c \\ 0 & 0 & 1/G_{ab} & 0 \\ -\nu_{ca}/E_a & -\nu_{cb}/E_b & 0 & 1/E_c \end{bmatrix} \qquad \ldots 3$$

where the suffixes a, b, and c refer to the principal directions of orthortropy, E and G = elastic and shear moduli, and ν = Poisson's ratio. The elastic modulus in the vertical direction and shear modulus are assumed negligible indicating only soil connection between reinforcement layers, and ν is taken as zero to indicate the open mesh reinforcing in each layer.

Rayleigh damping is used with the damping coefficients determined from the natural frequencies of the structure - medium system. The Wilson θ - Method is used for the step-by-step integration in time. The incremental and integration procedures are given in detail in Ref. 18.

NUMERICAL ANALYSIS

The media patterns and material properties considered are given in Fig. 1 and Table 1. Table II gives the results of the static and dynamic analyses. The time step used for dynamic analysis, 0.15 sec, is less than a tenth of the period of the third mode. The dynamic load pulse and displacement response, at three points in the containment, are given in Fig. 2. Fig. 3 shows the principal stresses in the containment and adjoining reinforced earth/clay medium, at an instant of time during dynamic loading. The total number of elements for the containment at 102 m depth is 208 with 433 degrees of freedom, and for the containment at 138 m depth, 256 and 523. Four to six-noded quadrilateral elements, and a 2 x 2 Gaussian integration scheme are used in the evaluation of mass and stiffness matrices.

DISCUSSION

The results confirm the increase in structural integrity due to embedment in mechanically strong material. A relatively weak soil has been considered in the medium, and results indicate little difference in the yield values for different burial depth and reinforced earth backfill. However, the introduction of a foamed concrete isolation jacket increased the initial yield values slightly (15.5 bars to 17 bars), and static ultimate load values considerably (18.75 bars to 27 bars). As the containment is much stiffer than the medium, it yields first. If a stiffening jacket is not provided, this leads to failure of the containment concrete. In view of its comparatively higher stiffness, the foamed concrete jacket (E = 2585.55 MN/m^2 to 39.23 MN/m^2 for clay) is able to provide additional confinement to internal pressurization. However, for dynamic loading, the peak internal pressure is not much higher than the static value at which first yield occurs. The rise time of the assumed load, 10 sec, is gradual compared to the fundamental period, 3.25 sec, of the system. This is the reason for the closeness of the dynamic values to the static ones in Fig. 2. It is observed that the steel in the reinforced earth does not reach yield values for the loading and structure considered. Hence, modelling the reinforced earth as a composite material, with linear orthotropic properties, is adequate for the problem solved.

Only the prestressing force and concrete are considered in modelling the containment. The ultimate load can be enhanced by considering reinforcing steel (material strong in tension) in the containment. Modelling similar to that applied to reinforced earth can be used. The linear orthotropic model used for the reinforcement can be extended to account for yielding of the reinforcement; it will be useful in the analysis of reinforced earth wall failures, where failure in the steel reinforcement have been reported.

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TABLE I. Material Properties and Configuration (Refer Fig. 1)

Concrete (C) Compressive strength, σ_{cu} = 44.13 MN/m^2; Tensile strength, σ_t = 5.75 MN/m^2; Modulus of Elasticity, E = 36285.9 MN/m^2; Poisson's ratio, ν = 0.2; Density, ρ = 2.4 Mg/m^3; Cohesion, c = 6.6551 MN/m^2; Angle of friction, ϕ=56.43°.

Foamed Concrete (FC) σ_{cu} = 9.087; σ_t = 2.11; E = 2585.55; ν = 0.3; ρ = 0.8; c = 1.94; ϕ=46.84.

Sandy Clay (S) E = 39.23; ν = 0.3; ρ = 2.0; c = 0.29; ϕ = 20.

Loose Sand (LS) E = 19.61; ν = 0.15; ρ = 1.6; c = 0.01; ϕ = 30.

Reinforcement RE1 E = 199949.2; % steel = 0.056.
RE2 E = 199949.2; % steel = 0.111.

CASE	ELEMENT GROUP											BURIAL DEPTH (m)	CONTAINMENT THICKNESS (m)
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI		
a	C											above ground	1.5
b	C	C										above ground	3.0
c	C	S	RE1 LS	S	RE1 LS	RE1 LS	S	S	S	S	S	102	1.5
d	C	S	RE1 LS	S	RE1 LS	RE1 LS	S	RE1 LS	RE1 LS	S	S	102	1.5
e	C	FC	FC	FC	RE1 LS	RE1 LS	RE1 LS	S	S	S	S	102	1.5
f	C	FC	FC	FC	RE1 LS	RE1 LS	RE1 LS	RE1 LS	RE1 LS	RE1 LS	S	102	1.5
g	C	S	RE2 LS	S	RE2 LS	RE2 LS	S	S	S	S	S	102	1.5
h	C	S	S	S	S	S	S	S	S	S	S	102	1.5
j	C	C	RE1 LS	S	RE1 LS	RE1 LS	S	S	S	S	S	102	3.0
k	C	S	RE1 LS	S	RE1 LS	RE1 LS	S	S	S	S	S	138	1.5
l	C	C	RE1 LS	S	RE1 LS	RE1 LS	S	S	S	S	S	138	3.0

NOTE: For cases k and l (burial depth 138m), a 36m soil layer overlies group XI.

TABLE II. Static/Dynamic Analyses

CASE	TYPE OF ANALYSIS	PRESSURE		YIELD LOAD (BAR)	ULTIMATE LOAD (BAR)	REMARKS
		INTERNAL (BAR)	PRESTRESS (BAR)			
a	static	linear increase	10	15 -17.5		All elements elastic for the sustained prestress case.
b			20	30 -35		
c			10	15.5-15.75	>18.75	
d			10	15.5-15.75	>18.75	
e			10	17 -17.5	>27	
f			10	17 -17.5	>25	
g			10	15 -17.5		
h			10	15 -17.5		
j			20	30 -35		
k			10	15 -17.5		
l			20	30 -35		
c	dynamic	15 (peak)	10			No failure
e		17.5 (peak)	10			No failure
e		20 (peak)	10			Failure at 12 sec

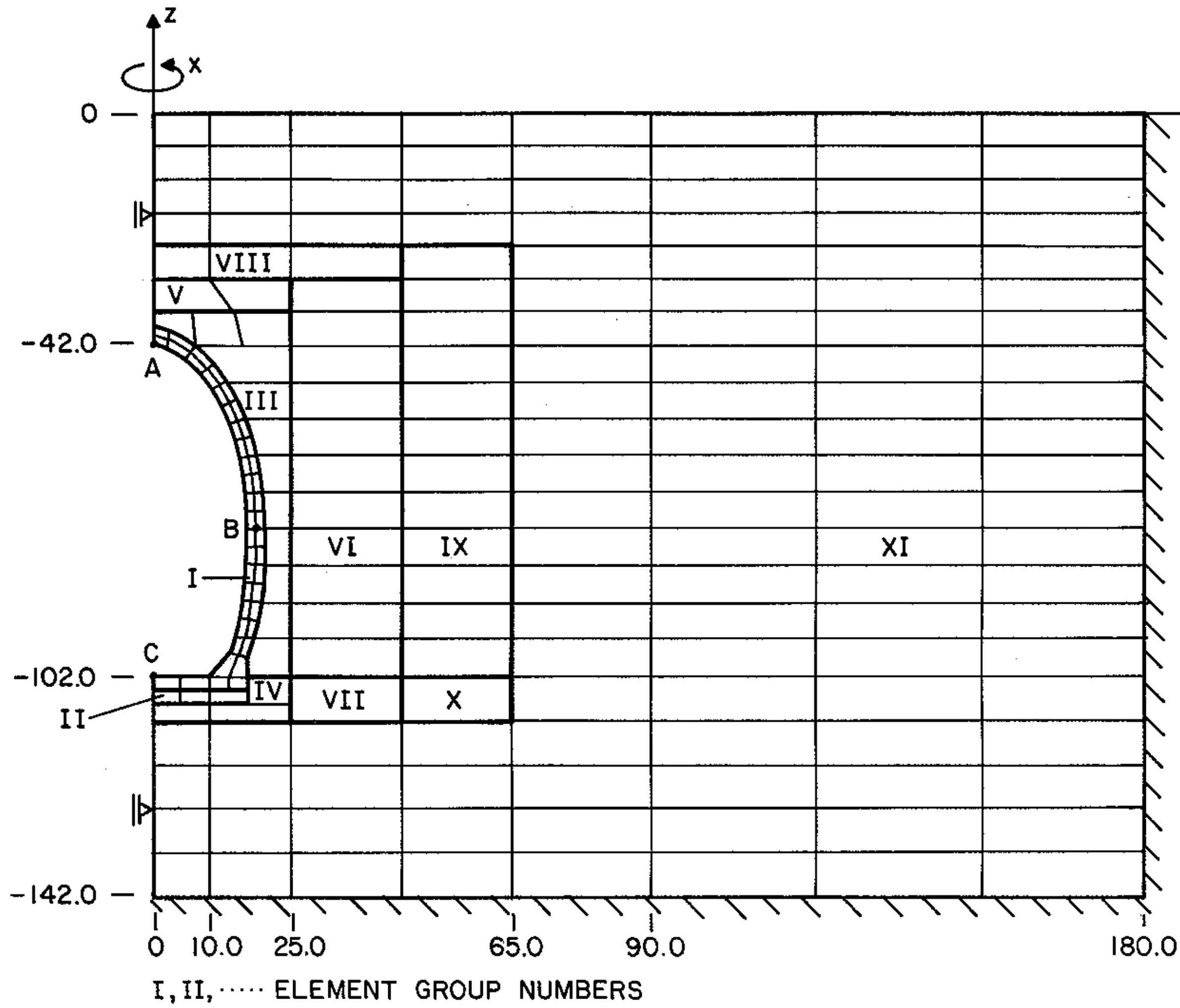

FIG. 1 Finite element idealization of containment at 102m depth.

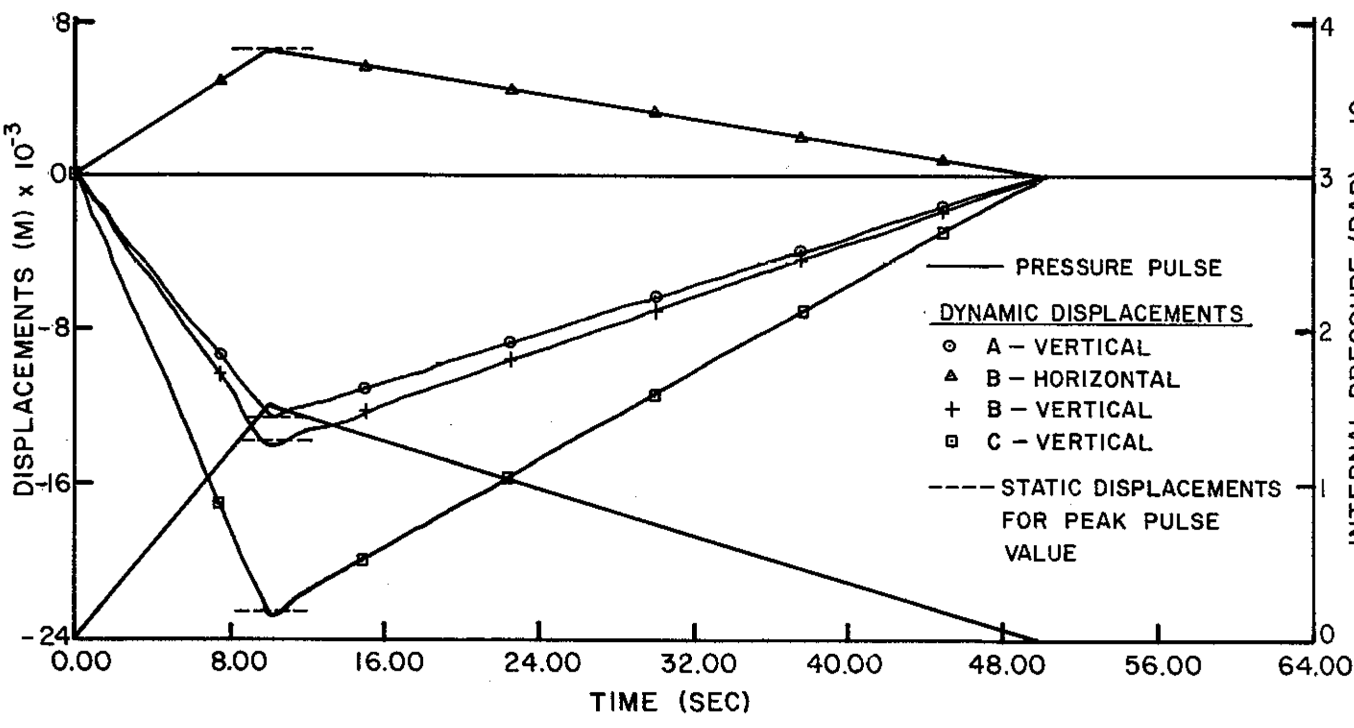

FIG. 2 Displacement response for peak internal pressure of 15 bars - Case c.

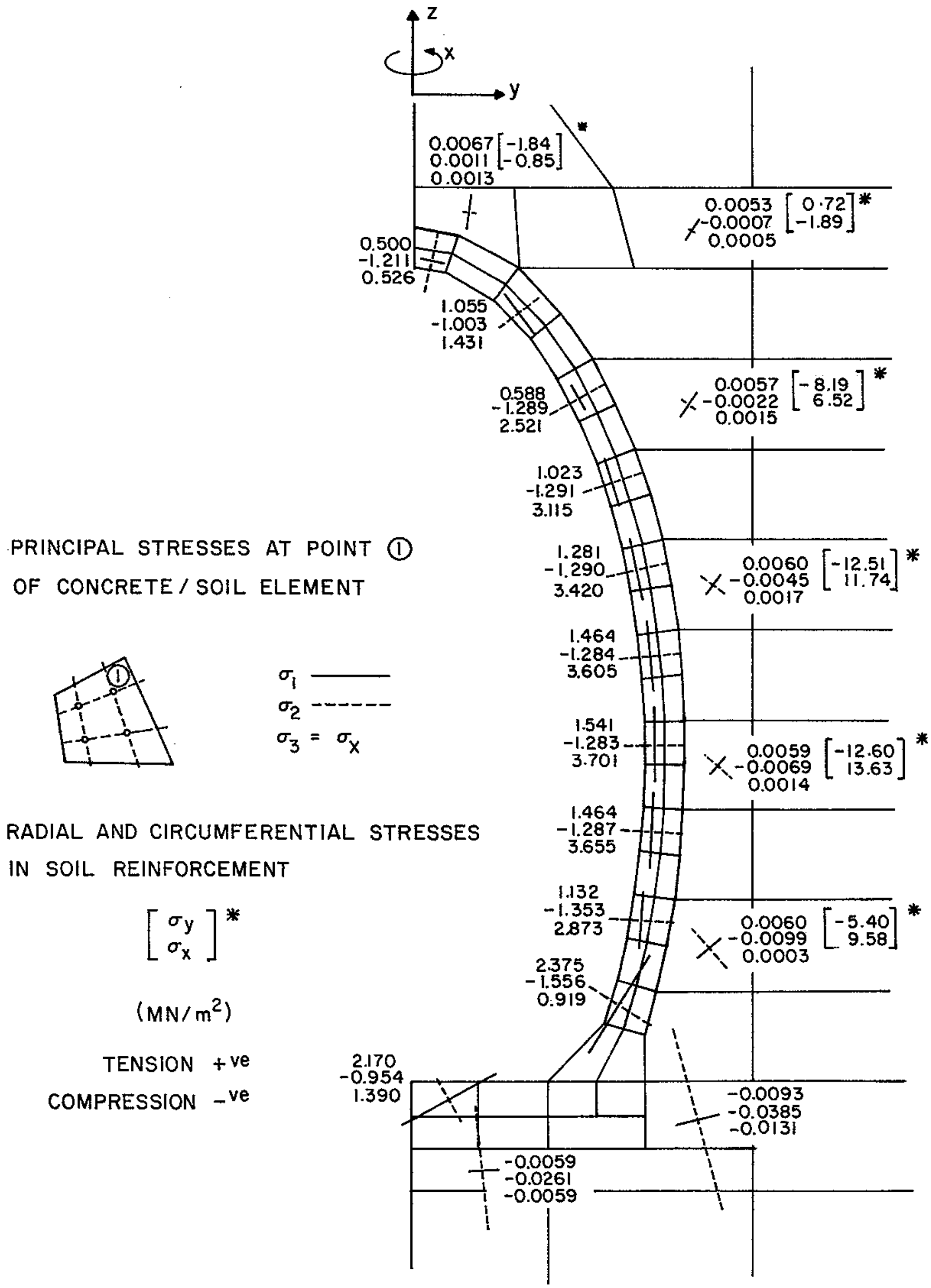

FIG. 3 Principal stresses in containment and adjoining medium, Case c - Dynamic response at 12 sec for peak internal pressure 15 bars.