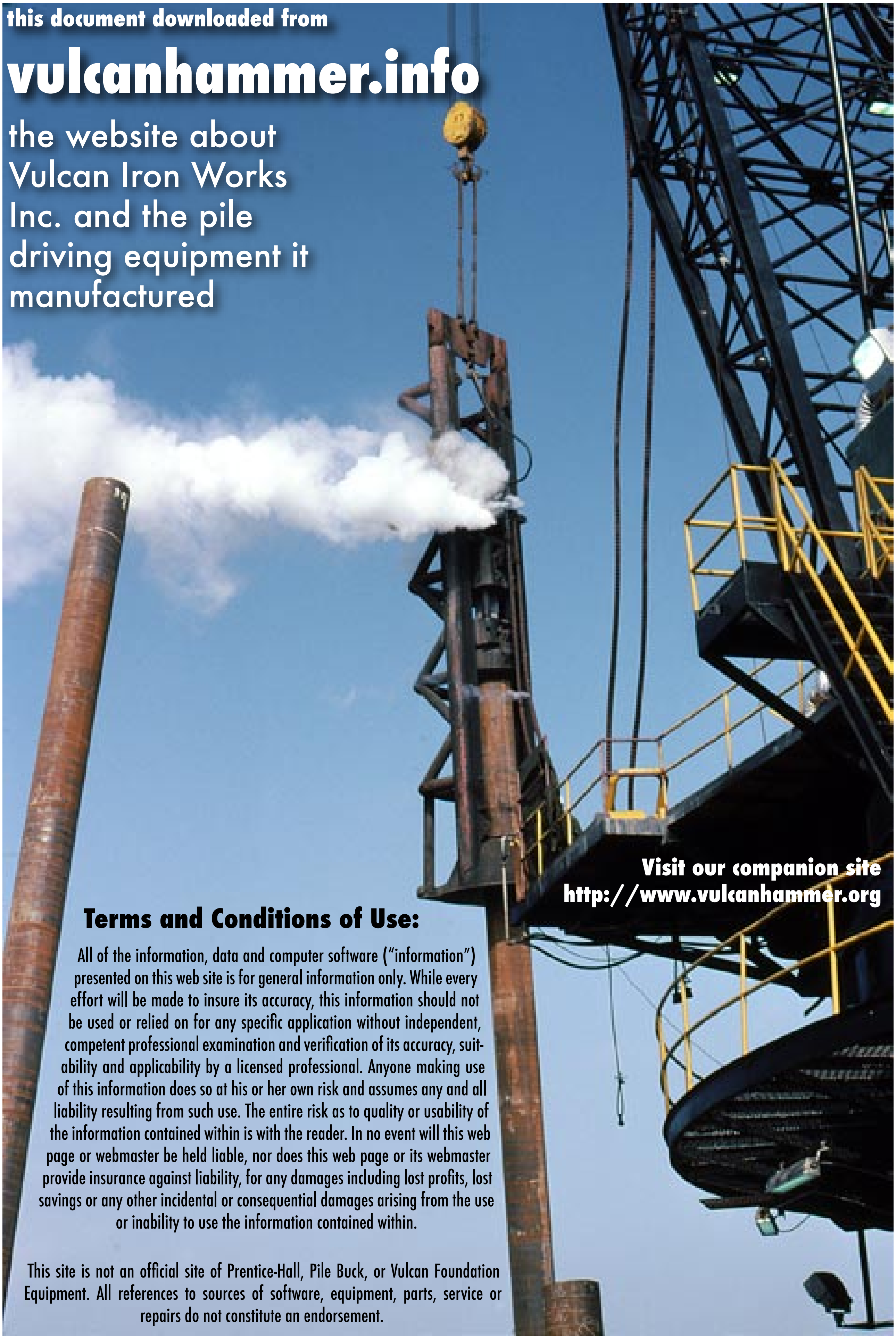

"ANALYTICAL INTERPRETATION OF PILE INSTALLATION AND AXIAL PERFORMANCE"

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Numerical Methods in Offshore Piling

The University of Texas at Austin

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ANALYTICAL INTERPRETATION OF PILE INSTALLATION AND AXIAL PERFORMANCE

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Synopsis

A program of combined experimental and analytical studies is presently underway with the purpose of extending present understanding of the axial behavior of pile foundations. The analytical developments are designed for backfitting and correlating the experimental results and for extrapolation to prototype designs. Emphasis therefore is placed on versatile and general-purpose computation tools which will permit examination of a wide variety of soil modelling concepts.

The experimental program includes laboratory and field model tests and full-scale pile load tests. Instrumented piles and pile segments are used to measure shear transfer, pore pressure, and total and effective stresses at the pile wall. Because current cavity expansion concepts have not yet explained changes observed during cyclic loading, a computation model has been introduced which enables axial shear and associated soil volume changes to be considered simultaneously with cavity expansion and lateral consolidation.

An economical radial assemblage of elements is used together with a two-phase model to account for both the soil skeleton and the pore water. Utilizing very general inelastic soil behavior characteristics, it is intended to investigate whether local volume changes, pore water migrations and changes in effective radial and circumferential stresses will or will not account reasonably for experimentally observed shear-zone degradation under cyclic loading.

The program is arranged to permit consideration of effective or total stress concepts, soil cohesion c, internal friction ϕ,

volume changes due to shear deformation or grain crushing, and creep and rate effects. Correlation studies are to include alternate approaches of (1) introducing measured soil properties for predictive analyses and (2) backfitting of experimental results to deduce the required soil properties.

For the solution of complete pile-soil systems, the results of the local cavity expansion and shear analysis may be used as a basis for estimating reasonable mechanical or rheological analogs to represent discrete soil supports along the pile. An available discrete-element program then may be used to predict load distribution, shear-transfer characteristics, soil degradation and ultimate capacity of a long offshore pile subjected to any prescribed pattern of static and cyclic axial loading.

Introduction

To meet the requirements of exploration and production in deep water a new generation of structural concepts is being evolved, including guyed towers, tension-leg platforms, and buoyant towers of various configurations. These concepts have in common the characteristics of extremely high cost of foundations and critical dependence on the security of the foundation performance. The concepts themselves represent major new technological initiatives, as contrasted to relatively continuous evolution of conventional jacket-type structures.

Each of the new deep water concepts imposes a new and different regime of static and cyclic loading on the foundation, and the piles tend to be very long because of heavy loading. To provide confidence in design, a clear and fundamental understanding of the behavior of the soil adjacent to the pile is essential. Data from simple ultimate static-load testing of short piles is not an adequate basis for design of such piles.

Behavior of Axially Loaded Piles

Some of the factors affecting side-friction capacity and deformational behavior of a pile are illustrated in Fig 1:

(1) In-situ soil stress conditions before pile installation.

(2) Changes in the soil conditions due to pile installation.

(3) Changes in the soil conditions from consolidation of the soil mass after installation.

(4) Changes in the soil conditions caused by subsequent static and cyclic axial loading.

As shown in Fig 1, the soil near the pile tip is remolded and displaced during pile installation. For a typical offshore open-ended pile, some amount of soil will enter to form the soil plug and some amount will be displaced laterally outside the pile wall producing a so-called cavity expansion effect. Cavity expansion is characterized by a significant increase of pore pressure at the pile wall which decreases with distance from the pile and decays with time. The pore pressure will dissipate to some degree even while the pile is being driven. After the pile is in place it may be subjected to static and cyclic axial loading, with possible cyclic degradation in a shear zone very close to the pile wall. It is essential to consider the effect of this shear zone on the performance of the pile foundation.

Current Analytical Approaches

Current practices of estimating the ultimate total side-friction capacity are based largely on empirical correlations derived from a limited number of pile load tests. Frictional capacity predicted by these methods can vary as much as 100 percent or more. To illustrate the level of uncertainties, pile capacities are calculated for a typical case by API rules, the Lambda method (Ref 18) and a version of the effective stress method suggested by Esrig, et al. (Ref 4). The comparison is given in Fig 2. It can be observed that predictions for short piles (less than 50 feet) are comparable for all three methods, but significantly different for very long piles. For example, at a penetration of 300 feet, pile capacities predicted by

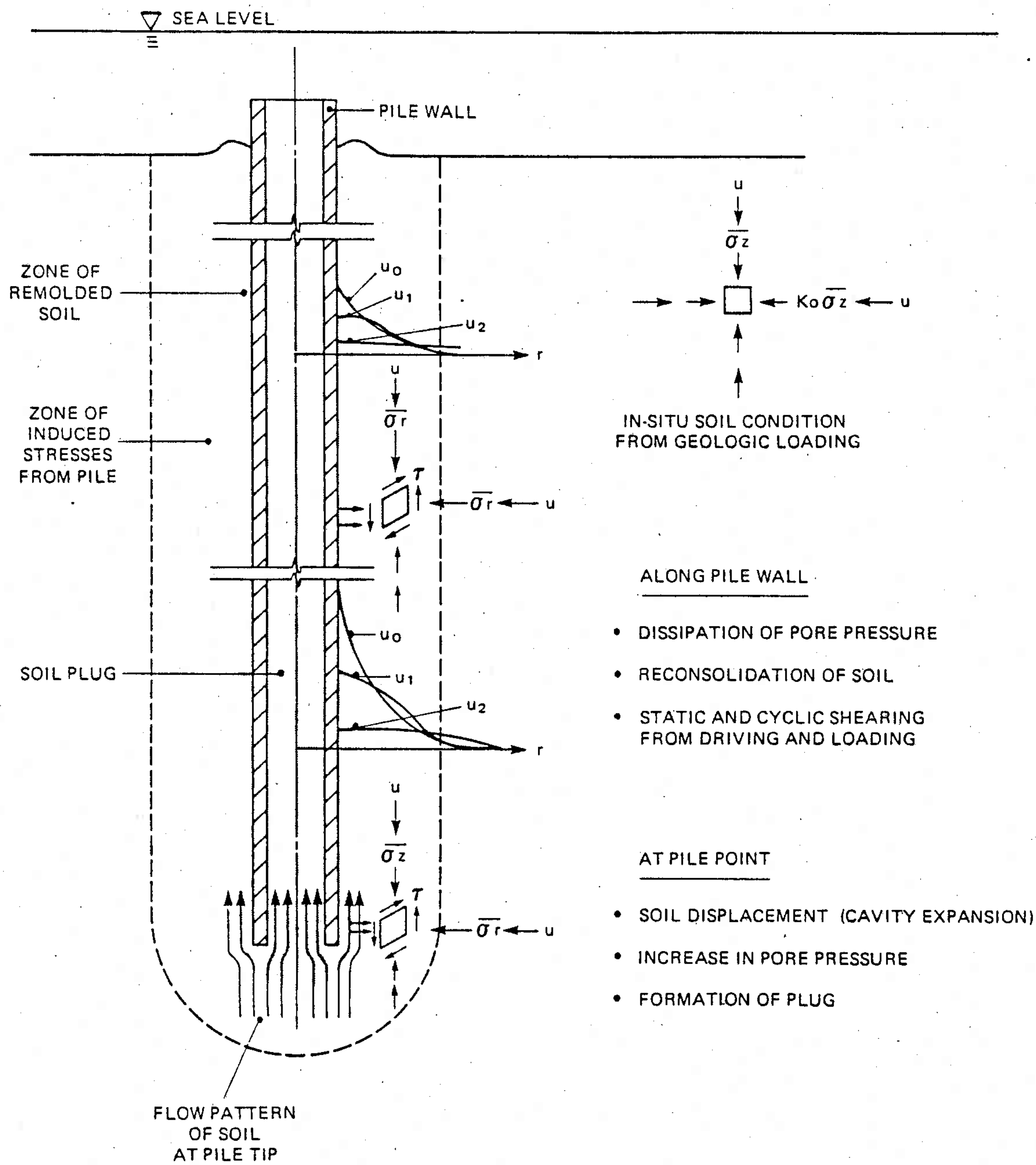


Fig 1. Description of pile loading process

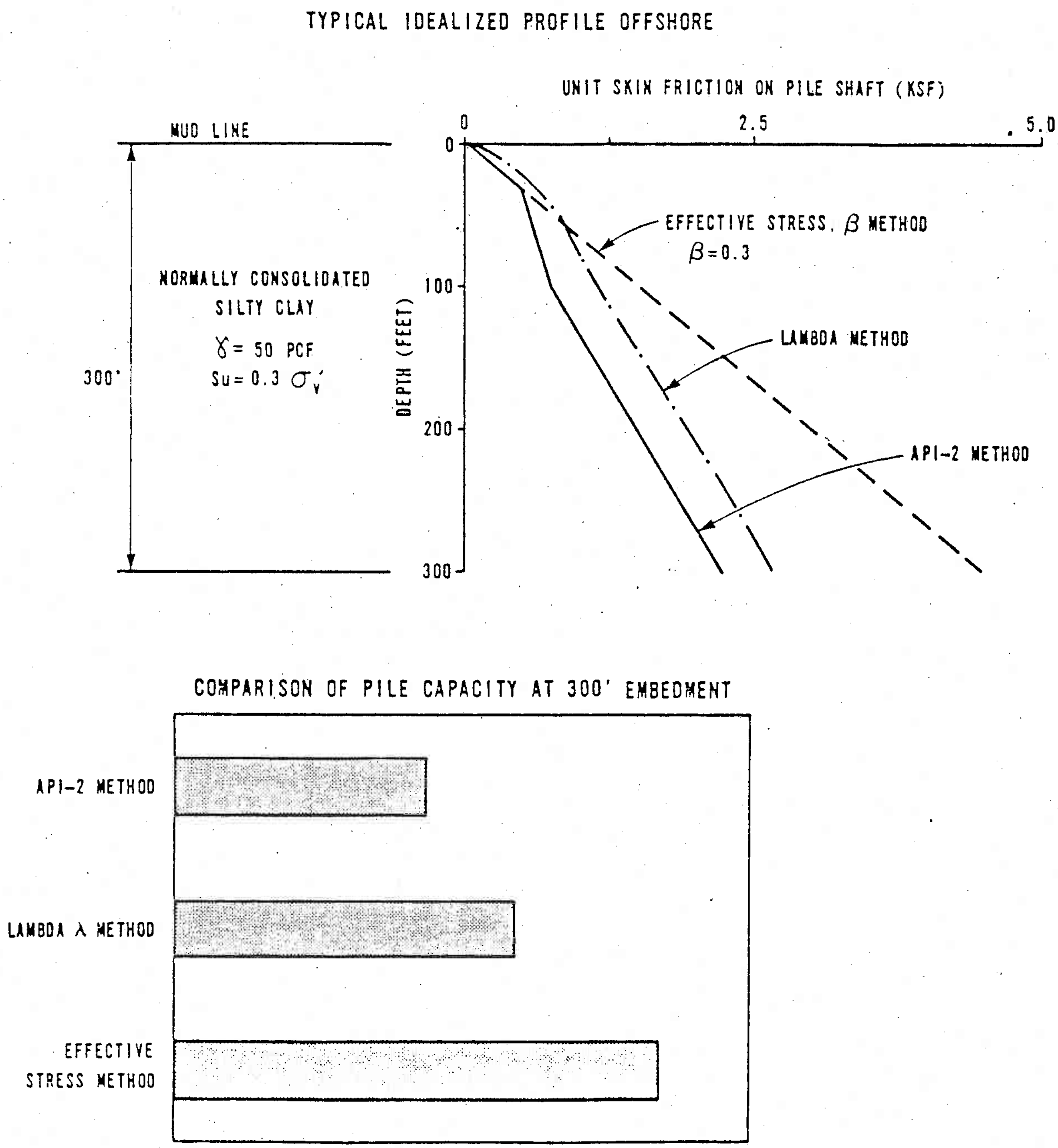


Fig 2. Range of uncertainty in axial pile capacity by different design criteria (after Matlock and Lam, 1980)

the effective stress method are nearly twice those from the API method. The wide range of uncertainty is largely due to the lack of field test data for very long piles but is also an indication of the fundamental limitations of present conceptual and analytical treatments of axial pile-soil interaction.

A large number of researchers (Refs 2, 3, 4, 5, 7, 13, 15 and 19) have attempted to predict pile capacity by estimating the radial effective stress and pore pressure changes due to pile driving and lateral consolidation. The pile installation process is modelled as the expansion of a cylindrical cavity with increase of pore pressure followed by lateral consolidation as pore pressure dissipates in the soil mass adjacent to the pile. The final values of effective stress at the end of consolidation are used to predict the skin friction capacity using effective strength parameters. A variety of constitutive models has been used to describe the soil behavior during these processes. The most widely recognized are the Critical State model used by both Esrig, et al. (Ref 5), Kirby, et al. (Ref 7) and the Modified Cam Clay model by Wroth, et al. (Ref 19).

These analytical developments have been very fruitful in the sense of stimulating consideration of axial pile behavior. However, they have not demonstrated accurate duplication of measurements from laboratory or field pile load tests either qualitatively or quantitatively. A comparison of measured and predicted lateral stresses for Boston Blue clay during lateral consolidation around an instrumented pile segment was presented by Ladd, et al. (Ref 8) and is shown in Fig 3. The measured radial stresses are much less than predicted values. For example, after consolidation and complete dissipation of excess pore pressure, the measured effective radial stress, and thus the estimated pile capacity, is only about one-third of the predicted value.

Parametric studies using conventional cavity expansion theory have revealed that the computed pile capacity is dominated by the constitutive model used to simulate the soil skeleton. One experimental study (Ref 1) has provided a strong indication that pile capacity under cyclic loading is controlled by degradation of the shear zone very close to the pile wall. Thus, a satisfactory constitutive model

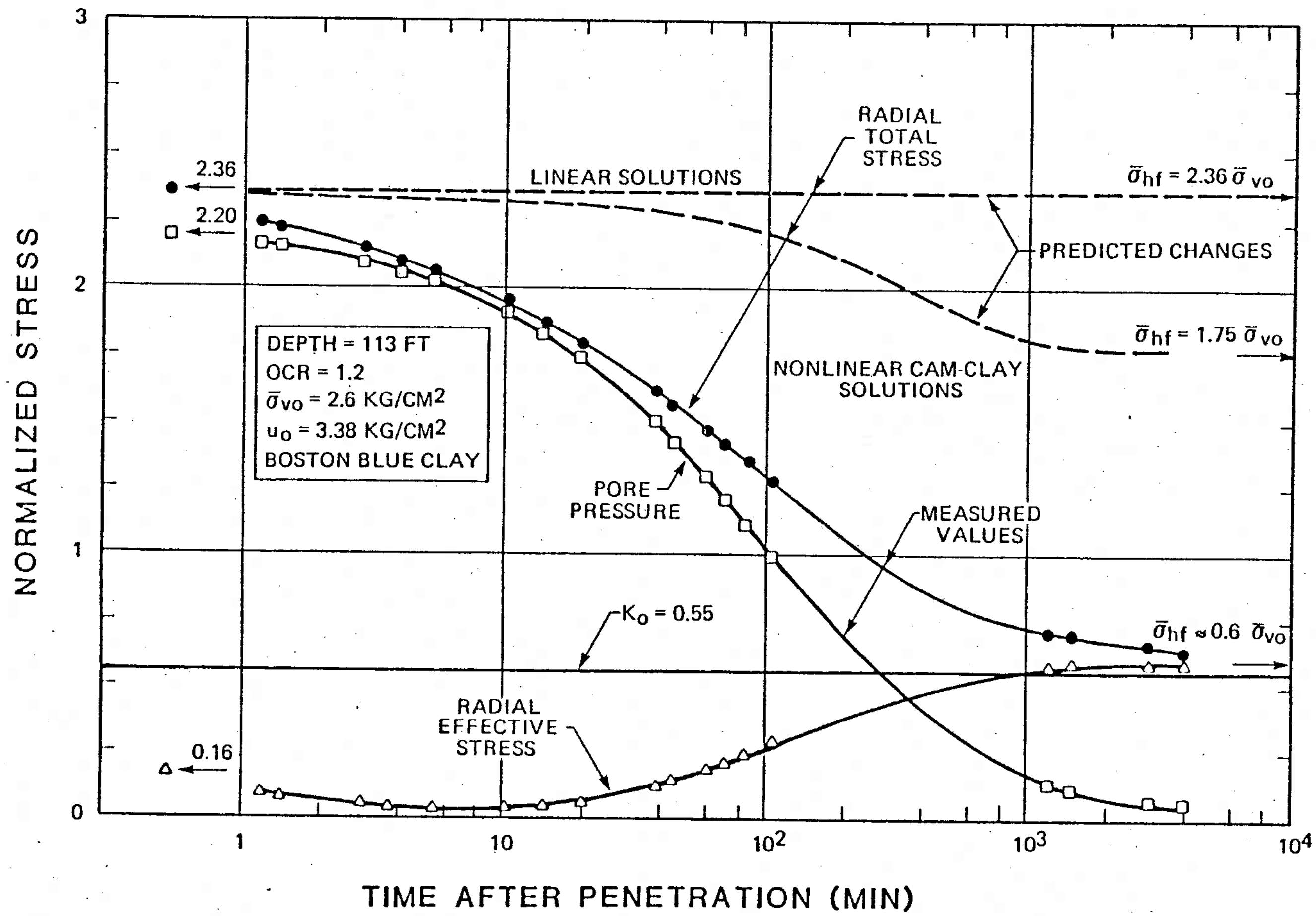


Fig 3. Measured and predicted changes of normalized stresses with time after pile installation (after Ladd et al., 1982, Ref 8)

should also simulate the changes near the pile wall that take place during pile driving and cyclic loading. Because of limited capabilities to handle inelastic and softening response, current treatments in constitutive behavior of soil do not appear to be adequate.

A Coordinated Research Program

In view of the continuing need for a practical, yet realistic approach for predicting deformational behavior and side-friction capacity of long offshore piles, a research program is being undertaken which emphasizes the coordinated use of both analytical and experimental approaches.

In addition to conventional sampling and laboratory testing, plus in situ testing, the experimental components of the program comprise

(1) laboratory model tests of pile segments,

(2) in-situ tests of pile segments, and

(3) field tests of full-length piles.

All of the experiments provide measurements of total lateral pressure, pore water pressure, and side-shear resistance of the soil as a function of static or cyclic axial displacement.

Versatility and economics of testing programs favor the laboratory segment tests which have been shown to duplicate cavity expansion and shear degradation effects of real piles (Ref 1). They are usually performed in remolded soil under artificial confinement. Much higher costs, but also a higher level of confidence in the applicability of the results, are associated with field tests of essentially full-size instrumented piles. Field testing of smaller instrumented pile segments provides a cost-effective intermediate-level approach. The advantages include insertion and testing in natural soils, comparative testing in parallel holes with assurance of excellent soil replication, and moderate costs which enable repeated testing with a variety of loading sequences.

In analytical developments, also, maximum benefits will be returned when an assortment of complementary approaches is employed. The methods presently being applied to pile behavior analysis include

(1) a solution of the complete pile-soil system employing discrete-element representations of soil supports,

(2) representation of local soil response with an axisymmetric solution of a horizontal soil slice, employing a two-phase cavity expansion and shear formulation, and

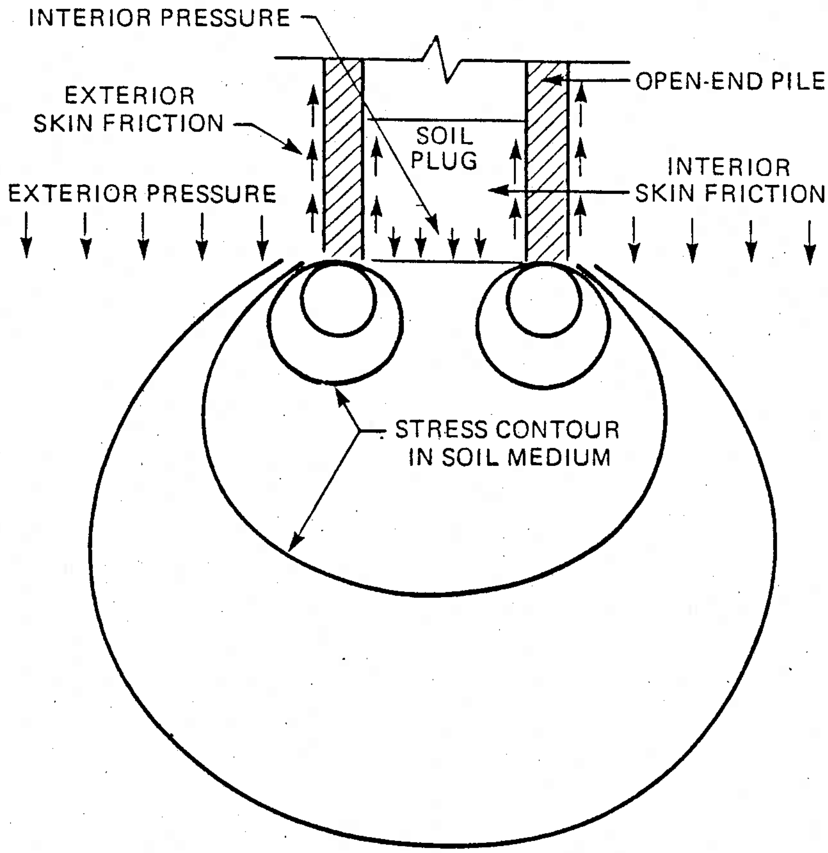
(3) a three-dimensional total-stress analysis of the plastic flow in the vicinity of the pile point during insertion.

The remainder of this paper is devoted primarily to these analytical developments, with emphasis on the second one. A computer program CASH (Cavity-expansion with Axial SHearing) has been formulated and is currently undergoing further development. In general, the choices of the analytical methods have been guided by the perceived need for flexible, general-purpose tools that can be adjusted or modified to fit the experimental observations and thus provide more confidence in interpretation and in application to the design of prototypes.

Soil Flow at Pile Point

During insertion of a pile, the flow of soil at the point represents the first influence of the pile on the soil. The degree of cavity expansion, that is, whether the soil is displaced totally outside a full-displacement pile or partially enters to form the plug of an open-end pile, would seem to be important to subsequent lateral consolidation, state of stress, and resistance to loading. However, a clear pattern of such influence has not been established. It is therefore tentatively planned that exploratory solutions will be made with DIRT II, a general utility finite element computer program (Refs 6 and 12) which is able to represent the soil as a single phase, nonlinear and rationally hysteretic medium.

Some very preliminary studies have been made with Program CASH using a two-phase elasto-plastic model for clay soil and imposing varying amounts of assumed radial displacement of the pile wall. This might be thought of as representing in a crude way variations of pile wall thickness. Some of the results are shown in Fig 4. The final effective lateral stress (and nominal pile capacity) appears to be most critically influenced by small initial expansions. Beyond the



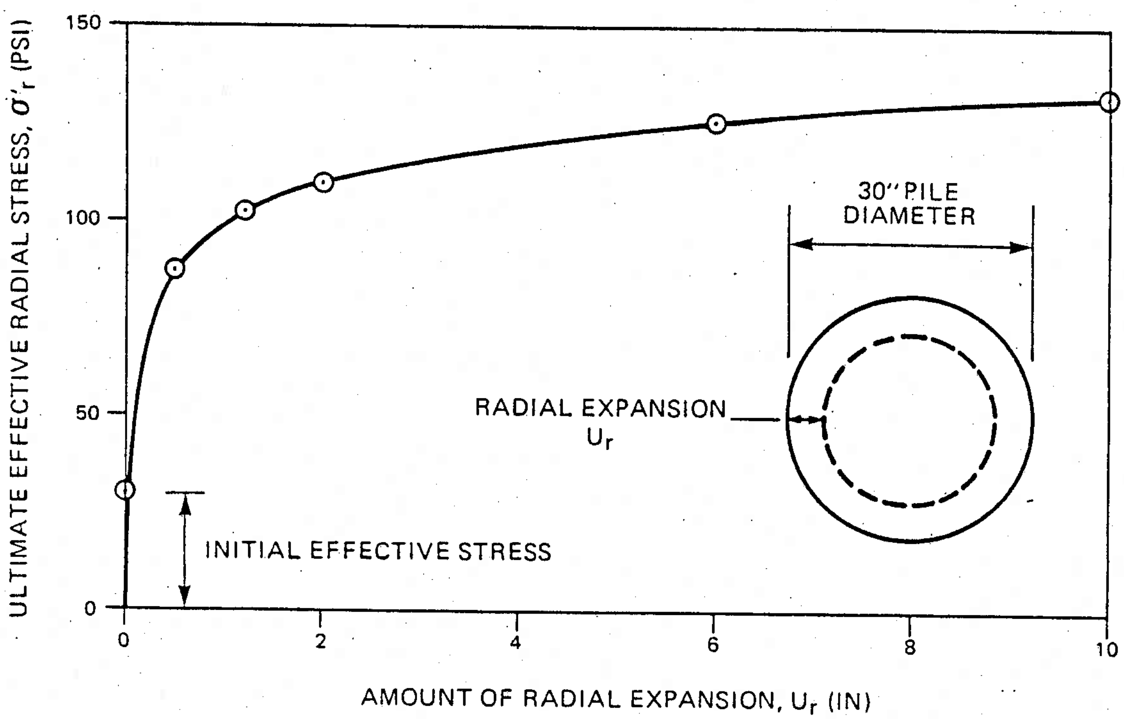


Fig 4. Ultimate effective radial stress versus amount of cavity expansion

first inch or two, the plastically sheared zone of soil around the pile increases in extent, but not much increase in final radial effective pressure is created.

Before undertaking an exhaustive (and possibly misguided) analytical study of the effects of soil flow around and into the point of the pile, it appears prudent to obtain some guidance from experimental observations. Accordingly, it is planned to perform some of the insitu tests on small-size pile segments in such a way as to compare closed-end and open-end insertions.

Solution for Complete Pile-Soil System

The performance of a long offshore pile can be analyzed using the computer program DRIVE (Ref 9). This program has been successfully used in numerous design and research oriented projects and provides the ability to consider, in natural sequence, multiple blows during driving and any desired subsequent pattern of static and cyclic axial loading. Fully hysteretic soil support behavior is represented and residual stresses are retained throughout the prescribed loading history. It is therefore particularly useful for predictions and correlations under real pile test conditions.

The mechanical analog used in DRIVE is shown in Fig 5. The pile is modelled by a series of discrete masses connected by elastic springs. Dash-pots are used to simulate internal and external viscous damping. For pile driving simulation, any number of the elements can be used to model hammer, cushion, anvil, and other components such as a long mandrel. The driving force may be applied to the pile at any prescribed point. Force-time pulses can be superposed freely.

Each axial support is modelled by an assemblage of elasto-plastic subelements, capable of representing a wide range of desired nonlinear and inelastic soil behavior. This soil support representation is shown in Fig 6, which demonstrates that the total resistance at any deformation is equal to the sum of the subelement forces. Soil degradation is simulated by reducing the resistance limit of subelements in accordance with prescribed effects of cyclic loading.

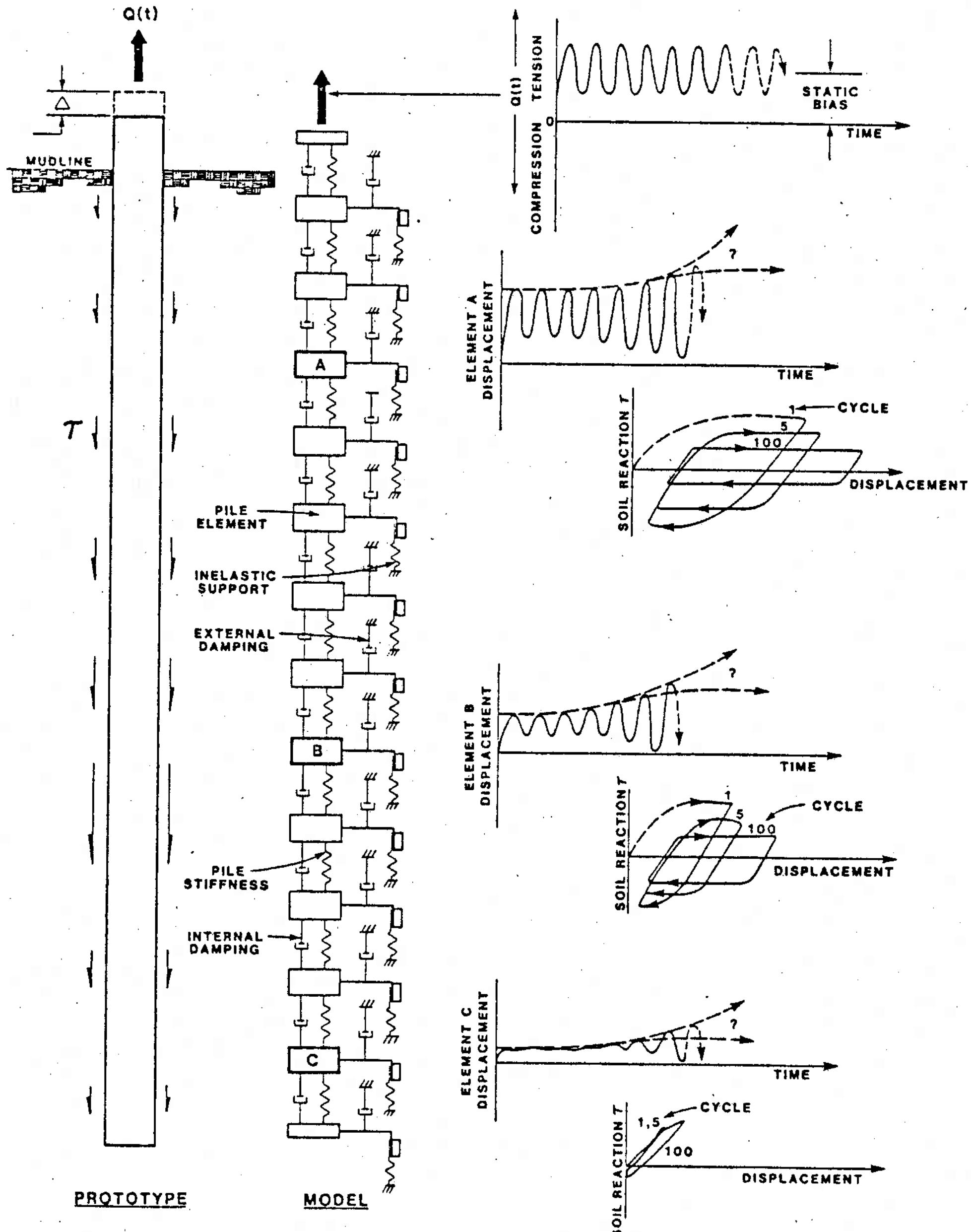


Fig 5. DRIVE model and progressive adjustments under cyclic loading

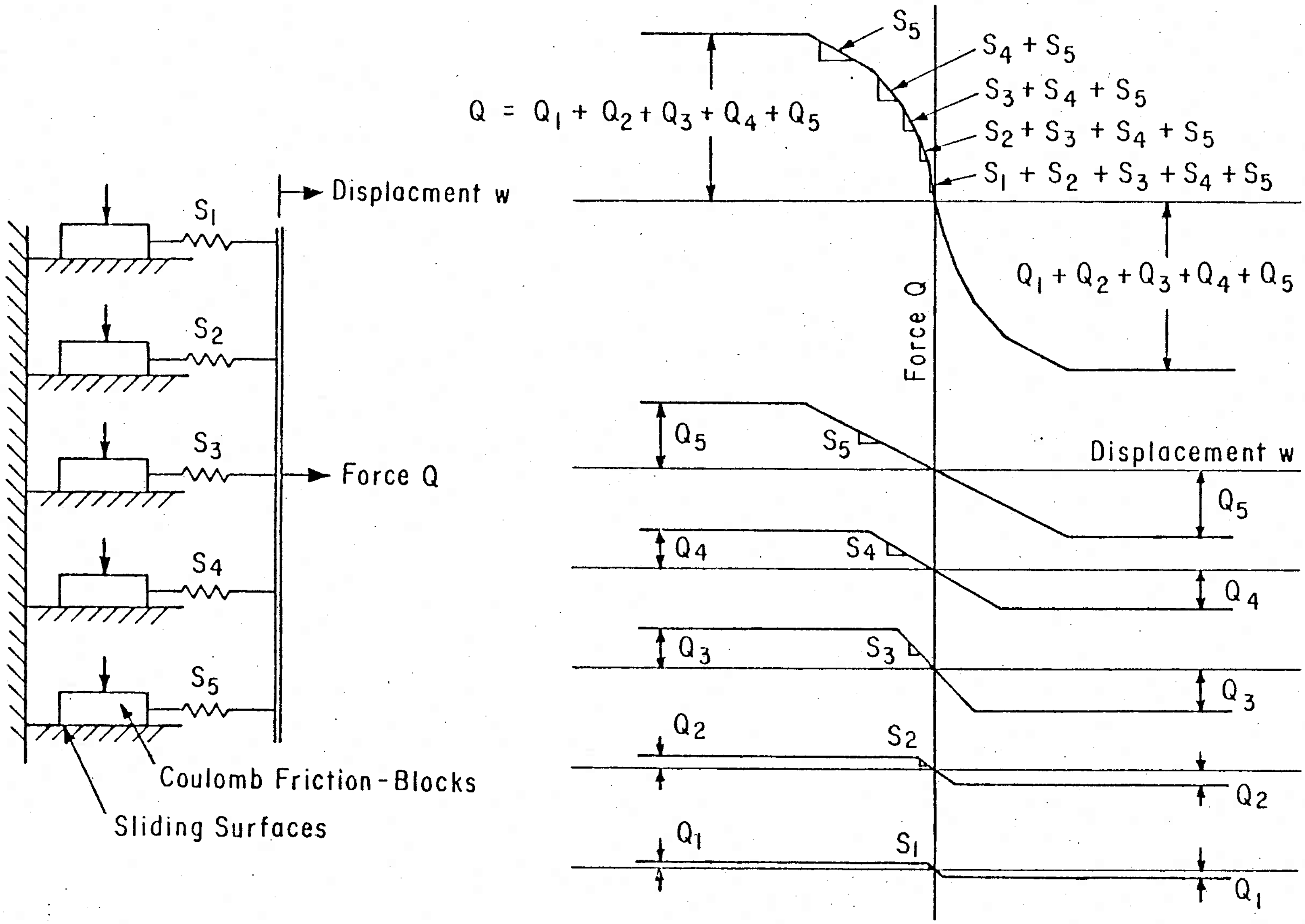


Fig 6. Sub-element model used in DRIVE (after Chen and Matlock, 1973)

Figure 5 also compares the possible responses of three suppports located at different depths. The long pile is subjected to loading conditions simulating an anchor for a tension leg platform. The initial behavior varies from large cyclic displacement and severe strength reduction near the mudline to pseudo-elastic soil response near the pile tip. Redistribution of displacement and soil resistance then progresses down the pile. Depending on the magnitude and duration of the cyclic loading, and the degree of progressive cyclic degradation, the pile may stabilize or may fail by pullout.

The DRIVE program is capable of examining this form of pile behavior provided that valid input data are available for the soil support models. Either the single-slice model of Program CASH or empirical t-z backbone curves and degradation parameters can be used as a basis for such soil support characterization.

Local Soil Support Evaluation

Program CASH enables consideration of the influences of (1) in-situ soil conditions, (2) pile installation, (3) lateral consolidation and (4) axial shearing. The results provide simulation of the side-friction characteristics of the soil surrounding a pile. Any combination of cohesion and internal friction may be prescribed.

Configuration. As shown in Fig 7, an axisymmetric single horizontal slice of soil mass surrounding a cylindrical pile is used for the analysis. Either a plane-strain or a plane-stress condition can be assumed in the analysis. Further refinement to reflect the elastic straining (stretching or compressing) of the pile under axial loading may also be incorporated into the analysis.

The slice of soil mass is discretized in the radial direction in terms of a radial dimension r . To allow for the internal generation of a very thin shear zone during axial loading, the increments are very finely spaced near the pile wall. To accommodate large displacement effects, the geometry (discretization) representing the slice of soil mass is updated with time.

Loading Conditions. Two components of a load-time history are used to simulate the effects of pile installation, consolidation and

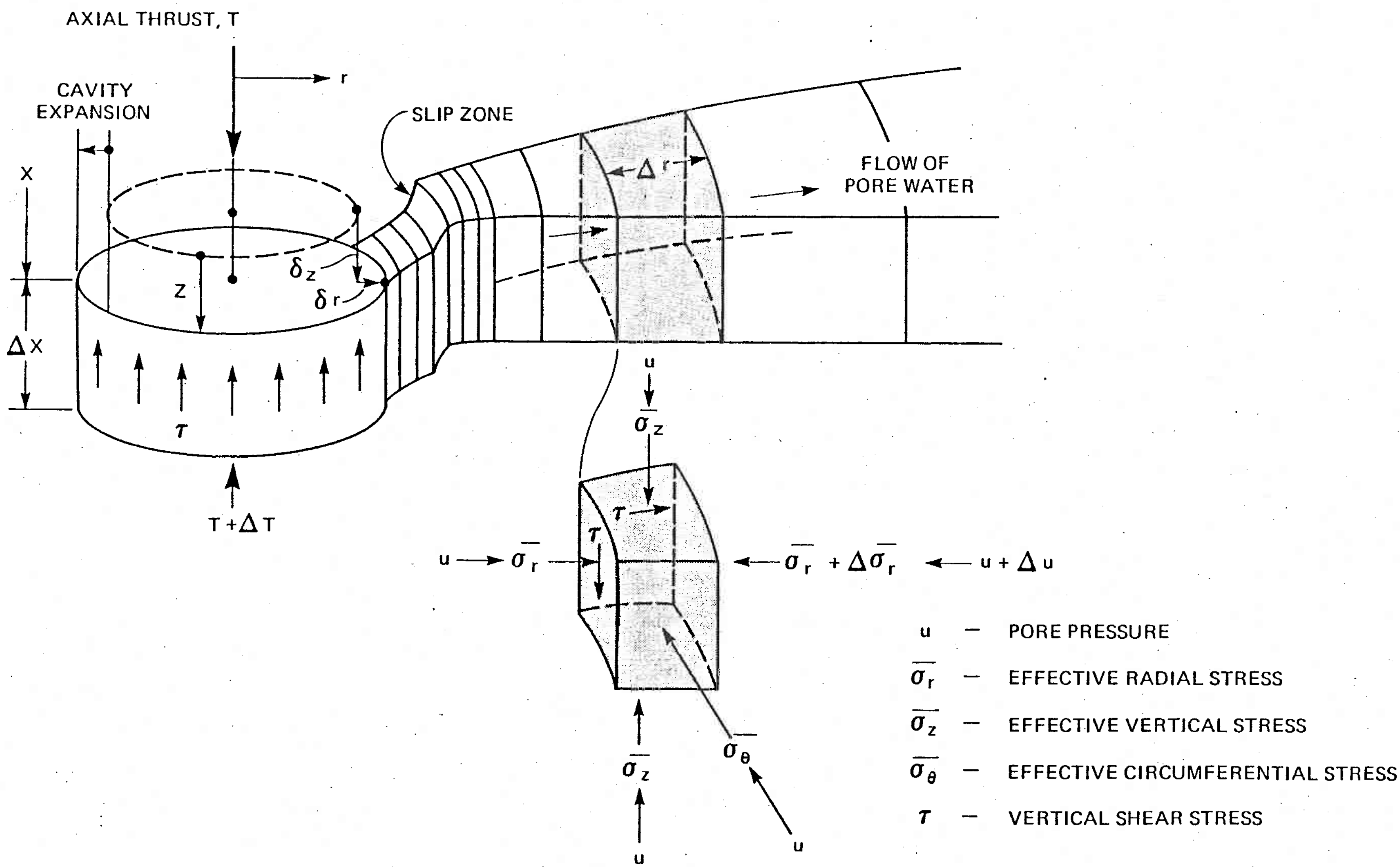


Fig 7. Single-slice model for pile installation, consolidation and loading simulation

axial loading. These time-dependent input functions are prescribed independently as radial (expansion) and axial (shearing) displacements at the cylindrical cavity wall. A variety of outer boundary conditions can be specified.

During actual pile driving, the soil close to the pile wall is repeatedly being sheared vertically, with considerable reversal near the top because of elastic rebound of the pile. Such shearing effects may have significant influences on the response and degradation of the soil close to the pile wall. The ability to prescribe axial shearing during pile installation is a major feature of Program CASH.

Degrees of Freedom. Displacement of the single-slice model is described by three degrees of freedom at each nodal point in the soil mass: (1) radial displacement u_r of the soil skeleton, (2) axial displacement u_z of the soil skeleton, and (3) radial displacment U_r of the pore fluid. During computation, the pore fluid movement at any point is characterized by its relative displacement with respect to the soil skeleton.

Two-Phase Saturated Soil Model. A two-phase effective stress model is used for the single-slice analysis. The stress condition at each point in the soil mass is characterized by an effective stress tensor σ'_r , σ'_z , σ'_Θ, and τ_{rz} plus a component of hydrostatic pore fluid pressure p .

The effective stress is the intergranular stress and the pore fluid occupies the pore space between soil grains. When the soil mass is subjected to an external load, the load distribution between the pore fluid and soil grains is governed by the classical Terzaghi effective stress concept (Ref 17):

$$\sigma = \sigma' + p \qquad (1)$$

where σ and σ' are respectively components of total and effective normal stresses and p is the fluid pressure.

In accordance with the effective stress and the two-phase soil model concepts, the effective stress of the soil skeleton is assumed to be dependent only on the strain components of the soil skeleton.

Similarly, the pore fluid may be nonlinear (but elastic). The pressure is assumed to be dependent on the total specific volume of the pore fluid. The bulk modulus of the fluid can also be used to simulate the presence of entrapped gas.

Constitutive Relation for Soil Skeleton

As stated, the major general requirement placed on the formulation of the constitutive relation is flexibility for backfitting and correlation of any observed pile load test data. Shear dilation or volume compaction and hysteretic shear deformation are accommodated in input data descriptions.

The stress-strain relationship used in Program CASH is written in the form of a modified plasticity model with empirical provision for volume change:

$$\sigma'_{ij} = \lambda\delta_{ij}(\varepsilon_v + \Theta) + 2G\varepsilon_{ij} + \sigma'^{R}_{ij} \tag{2}$$

where λ is Lame's constant,

G is the shear modulus,

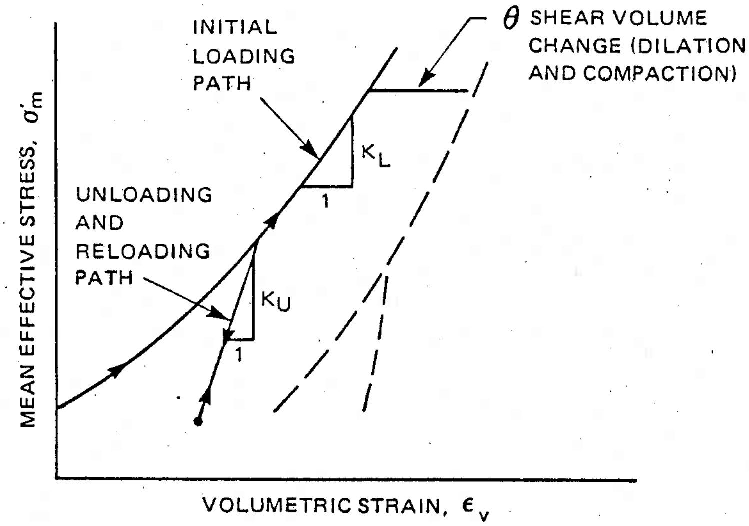
δ_{ij} is the Kronecker symbol,

ε_v is the volumetric strain,

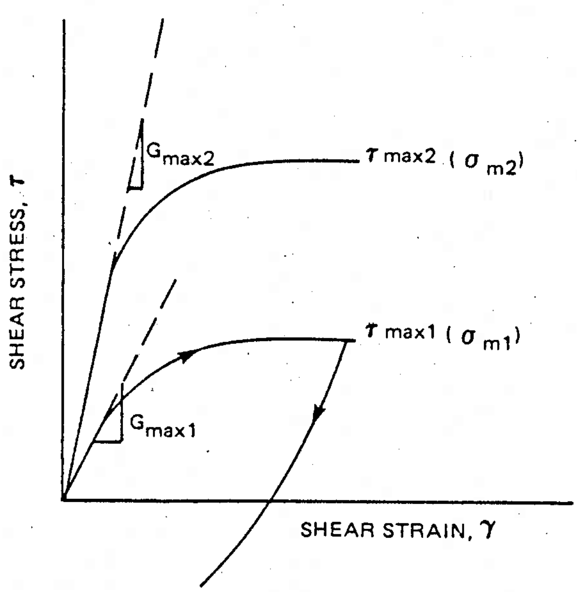
Θ is a scalar variable which can be used to control any volumetric effects including dilation and compaction, and,

σ'^{R}_{ij} is a stress vector used to introduce shear failure effects.

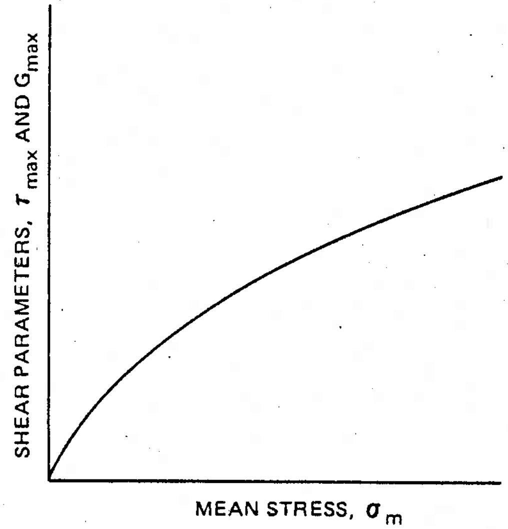
The stress-strain model is schematically described by Fig 8. Clearly, stresses σ'_r, σ'_Θ and p could be significantly affected by volumetric expansion or contraction in the shear zone. Therefore, the constitutive model must allow for considerable flexibility in input descriptions of soil characteristics. Compatibility and equilibrium must be finally achieved for all components of the system but considerable freedom is allowed in describing the soil characteristics. As shown in Fig 8(a), the volumetric behavior is characterized by nonlinear and inelastic stress-strain curves.



(a) VOLUMETRIC BEHAVIOR



(b) SHEAR BEHAVIOR



(c) RELATIONSHIP OF SHEAR PARAMETERS ON CONFINEMENT

Fig 8. Input description of soil model

Furthermore, the model allows for differences in stress history between initial loading, unloading and reloading conditions. A flexible framework for shear-volume coupling behavior is also of primary importance. Volume change due to shearing is reflected by the translation of the volumetric stress-strain curve, controlled by the parameter Θ . This parameter can be monitored to reflect monotonic behavior such as shear dilation and compaction as well as volume change from cyclic loading, including grain crushing.

As shown in Fig 8(b), the shear behavior of the proposed model is characterized by a nonlinear stress-strain curve that is capable of simulating hysteretic and failure characteristics of the soil. The proposed soil model also allows for varying stiffness and ultimate failure levels for different confinements as shown in Fig 8(c).

In Program CASH, all variables λ , Θ and G , as well as most failure criteria, can be described by the user. The program uses an iterative approach to ensure that the closure error is tolerable, even for a large loading increment. Most effective-stress soil models can be incorporated as connecting subroutines into Program CASH.

<u>Constitutive Relation for Pore Fluid</u>. A bulk modulus K_f is used to relate pore fluid pressure to volume. The conventional equation of state of the fluid is used:

$$\Delta p = K_f \left(\frac{\Delta\gamma_f}{\gamma_f} \right) \tag{3}$$

where Δp is change in pore fluid pressure and γ_f and $\Delta\gamma_f$ are the current density of the fluid and the change of density, respectively.

Change in density of the pore fluid during loading is computed by keeping track of the change in total volume as well as the change in porosity (available pore space in the soil skeleton):

$$\frac{\Delta\gamma_f}{\gamma_f} = \Delta\varepsilon_f + \Delta\varepsilon_s \frac{\Delta n}{n} \tag{4}$$

where $\Delta\varepsilon_f$ is the specific volume change of the pore fluid,

$\Delta\varepsilon_s$ is the specific volume change of the soil skeleton, and

n is the porosity.

Governing Equations. There are three governing equations for the single-slice soil model. They arise from considerations of:

(1) static equilibrium in the radial direction,

$$\frac{\partial \sigma'_r}{\partial r} + \frac{\sigma'_r - \sigma'_\theta}{r} + \frac{\partial p}{\partial r} = 0 \qquad (5)$$

(2) static equilibrium in the axial direction,

$$\frac{\partial \tau_{rz}}{\partial r} + \frac{\tau_{rz}}{r} = 0 \qquad (6)$$

and (3) Darcy's Law for flow of pore fluid in the radial direction

$$\frac{\partial p}{\partial r} + \frac{\gamma_f}{k} \Delta \dot{U}_r = 0 \qquad (7)$$

The three equations are written at each interior nodal point of the discretized soil mass model, resulting in a system of simultaneous equations that are solved implicitly and iteratively at each loading step. The equations are expressed in terms of the three components of displacement (three degrees of freedom) at each of the nodal points. These displacements are related to the stress components and pore pressure through the displacement-strain and the stress-strain (constitutive) relationships, as described above.

Example Using the CASH Program

An example problem is used as a very preliminary demonstration of the capability of the described analytical procedure. A pipe pile, 30 inches in diameter with a wall thickness of 1.2 inches, is assumed to be driven with an open end. The soil is assumed to be silty clay.

Although the CASH program is structured for versatility in handling of stress-strain behavior, a very simple soil description is used for the following example. The volumetric behavior is assumed to be linearly elastic and the shearing behavior is elasto-plastic. The input parameters for the example problem are summarized below:

Shear modulus, G = 6400 psi
Poisson's ratio, ν = 0.3
Cohesion, c = 1.0 psi
Friction angle, ϕ = 30 degrees
Vertical effective stress, σ'_v = 30 psi
Earth coefficient at rest, k_o = 0.5
Unit weight of pore fluid, γ_f = 0.036 pci
Permeability, k = 1.0×10^{-6} in/sec
Initial void ratio, e_o = 0.5
Pore fluid bulk modulus, K_f = 3.0×10^5 psi

The loading conditions prescribed at the soil-pile interface were selected to simulate (1) pile insertion, (2) local consolidation and (3) soil response under axial shearing both during and near the end of consolidation. The selected input displacement-time functions are shown in Figs 9 and 10. The expansion of the cavity was completed in 3 seconds at a rate of 0.4 inch per second. Three seconds after full expansion, one-half cycle of axial shearing with displacement amplitude of 2.0 inches and period of 8 seconds, was applied to study the soil response immediately after pile installation. At some intermediate stage of consolidation, a similar half cycle of axial shearing was applied to compare the effects after excess pore water had nearly dissipated. The results of the analysis are summarized in the following paragraphs.

Pore Pressure and Effective Radial Stress Distribution. The pore pressure and effective radial stress distribution are shown respectively in Figs 9 and 10. As shown in Fig 9, the excess pore pressure gradually dissipates during consolidation with an increase near the pile wall during axial shearing. The radial effective stress distribution shown in Fig 10 indicates a gradual increase during consolidation, resulting in higher shear resistance at the pile wall after

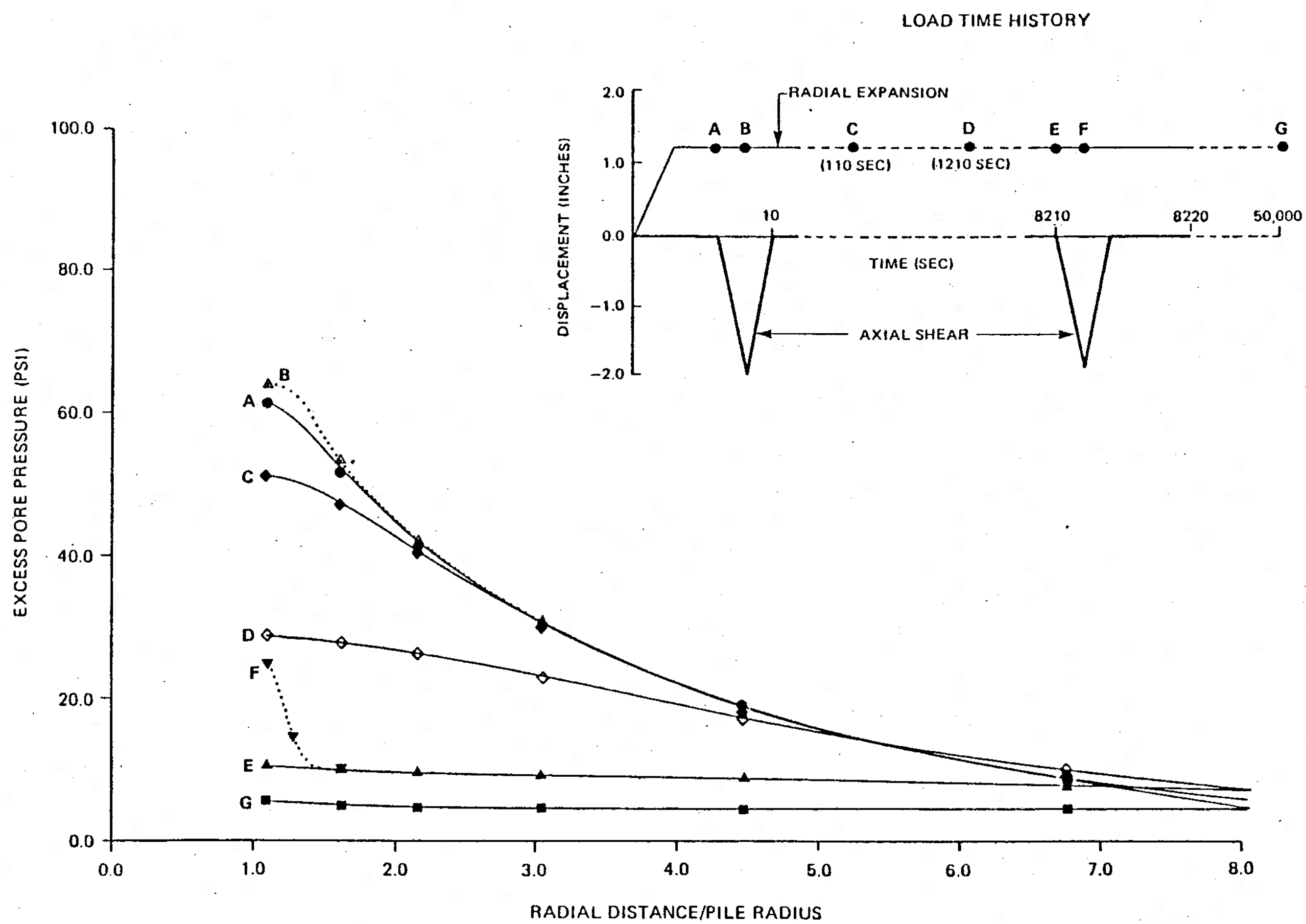


Fig 9. Computed excess pore pressure distribution

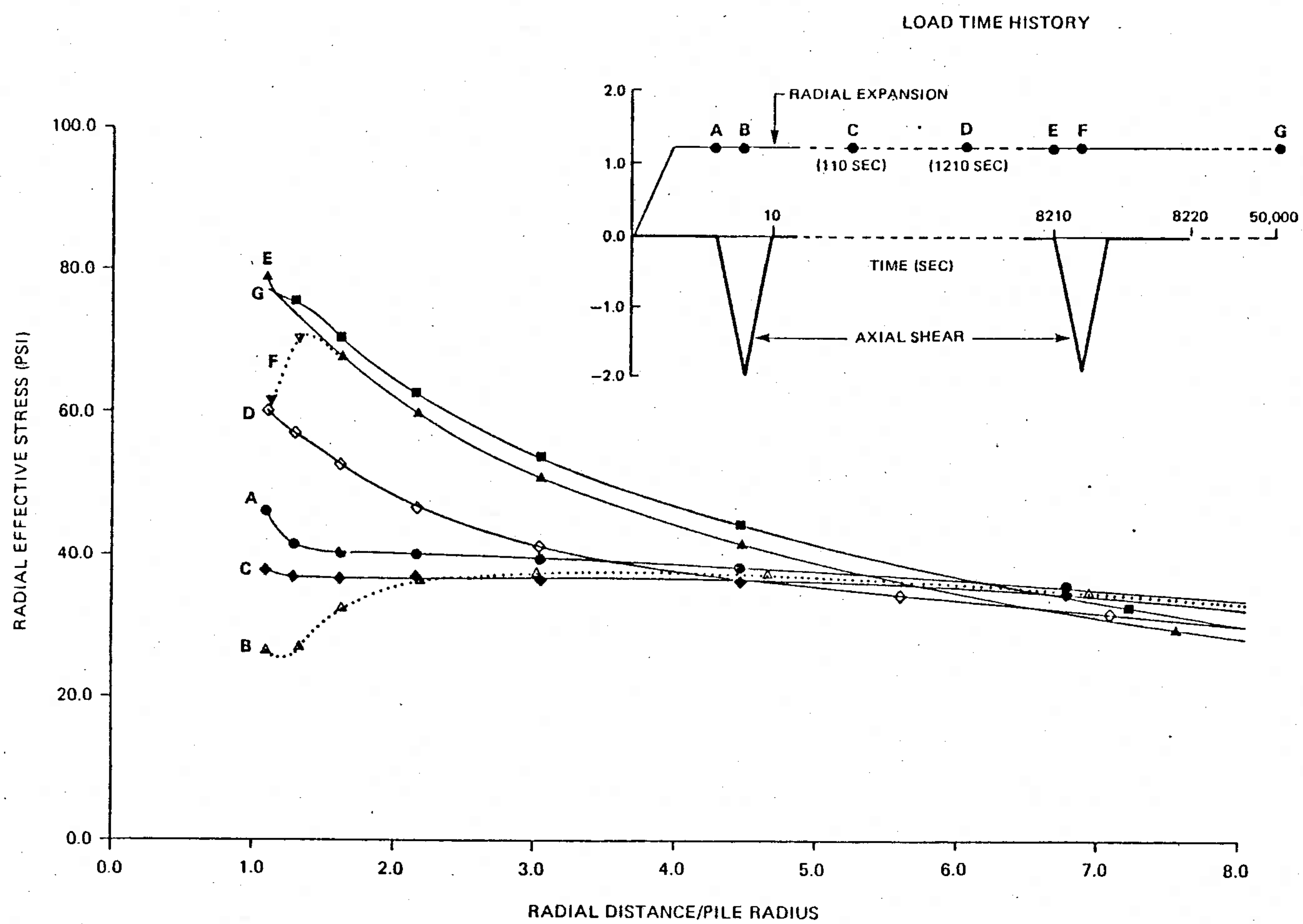


Fig 10. Computed effective radial stress distribution

consolidation. During inelastic axial shearing, the radial effective stress depresses near the pile wall.

The maximum excess pore pressure is about 64 psi, which is equivalent to about two times the initial effective vertical stress. Figure 9 also reveals a very fast rate of dissipation during the early part of lateral consolidation due to a relatively high hydraulic gradient at the pile wall. It should be noted that during axial shearing, some amount of pore pressure increase was generated very close to the pile wall due to the inelastic soil response. The radial effective stress (Fig 10) changes only slightly from the initial condition during expansion, reflecting basically an undrained expansion process; most of the applied load is resisted by the relatively incompressible pore fluid.

The solution of shear transfer versus axial displacement at the pile wall is presented in Fig 11. It can be seen that the side-friction capacity is increased as a result of the consolidation process. Such shear-transfer characteristics at different depths along the pile can be obtained from separate single-slice analyses and be used as input to the DRIVE analysis.

Time History Solutions. The complete time histories of pore pressure and effective radial and circumferential stresses at the pile wall are further summarized in Fig 12. The soil behavior is elastic for the initial 0.4 inch (1.0 sec) of radial expansion. It is characterized by an increase in radial effective stress, but a decrease in circumferential effective stress. Since the shear resistance is limited by the shear strength at the initial confining stress level (before pore pressure dissipation and consolidation), additional forces from radial expansion beyond the elastic range are transferred to the pore water. This transfer results in an increase in pore pressure, but small changes in effective radial and circumferential stresses are shown from points 0 to A in Fig 12.

Shortly after full radial expansion, a cycle of axial shearing was applied from 4 to 10 seconds as shown in Fig 12. During shearing (points A to B), some permanent inelastic shear yielding occurs, resulting in an increase in pore pressure and circumferential stresses, but a decrease in radial stress.

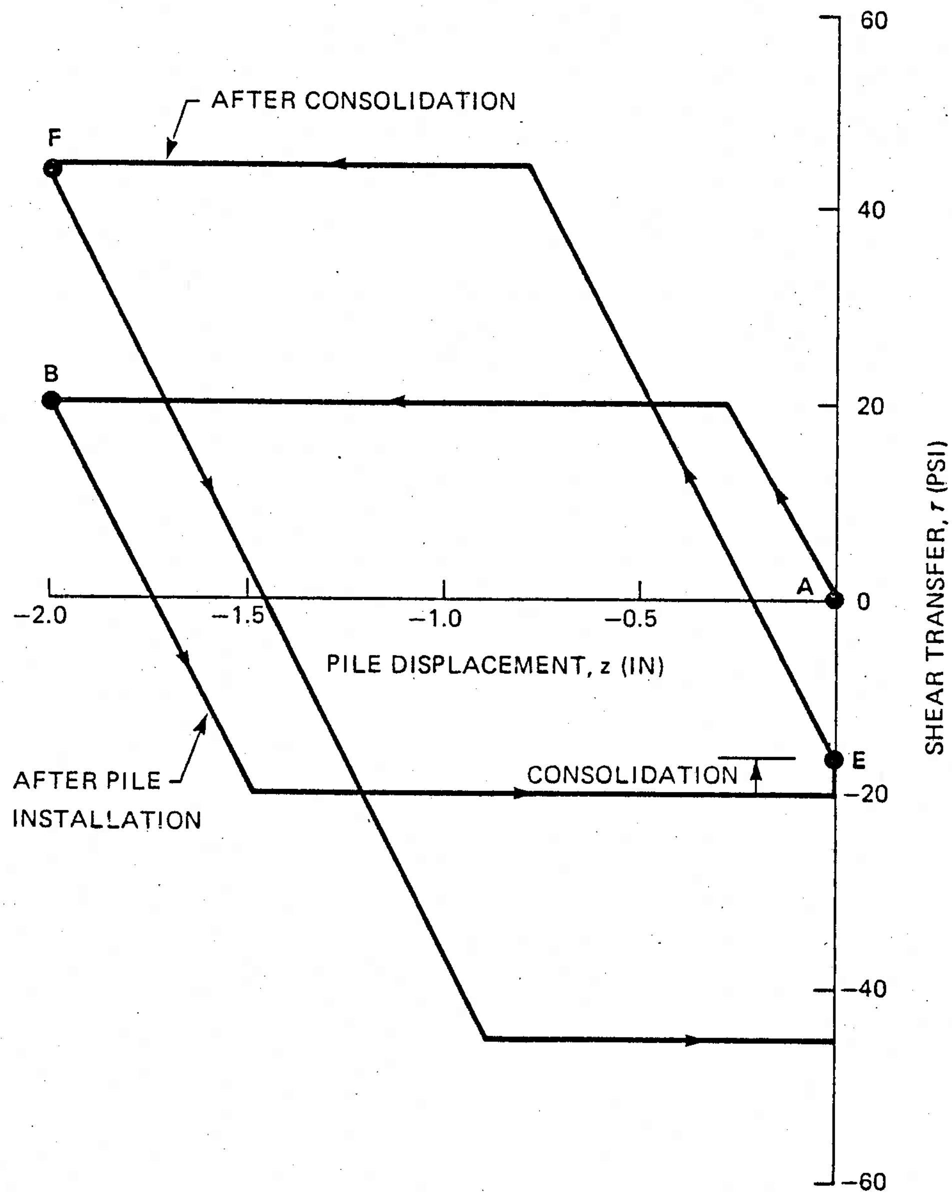


Fig 11. Vertical-plane shear transfer displacement relationship obtained by single slice model

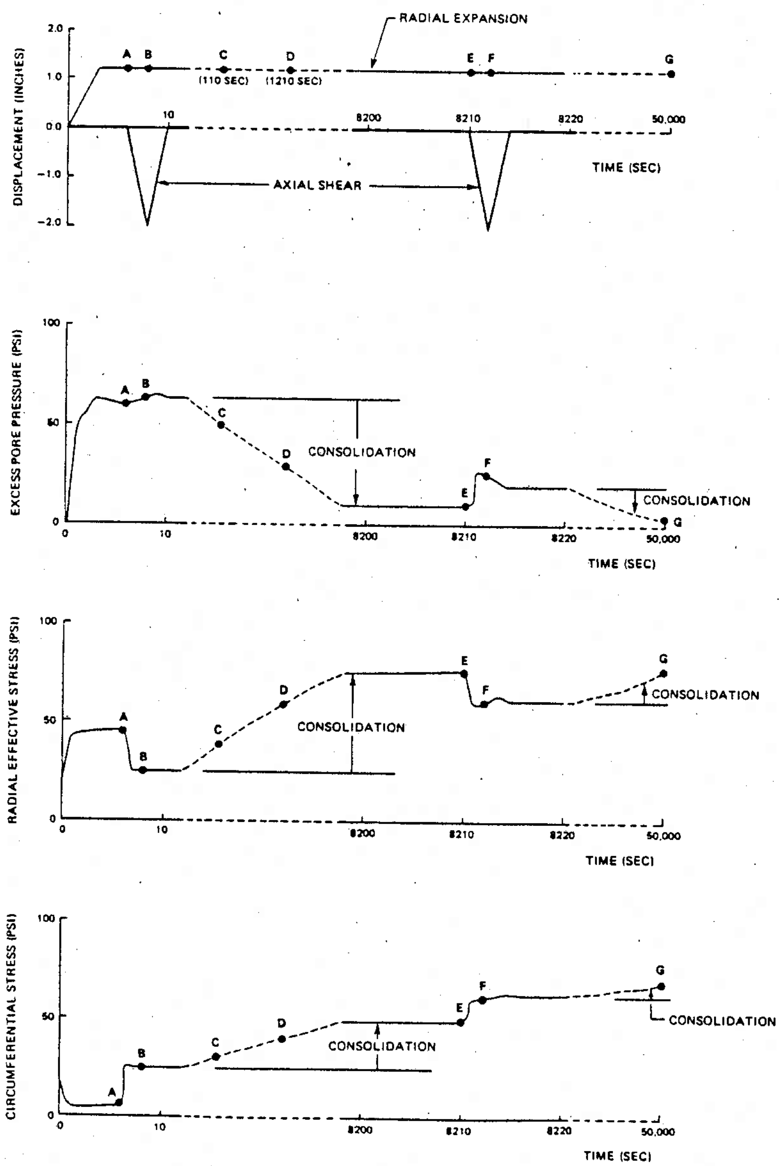


Fig 12. Excess pore pressure, effective radial and circumferential stresses variation with time at pile wall

Throughout the cavity expansion and axial shearing (zero to 10 sec.), consolidation of the soil mass is occurring continuously. However, the consolidation effect is not significant initially due to the short time duration. The consolidation effect is more pronounced between points C and D in Fig 12, which shows a 50 percent reduction (dissipation) of pore pressure together with increases in both radial and circumferential effective stresses.

As shown from points E to F in Fig 12, a second cycle of axial shearing was applied at some intermediate stage of consolidation. The general behavior for this cycle of shearing is quite similar to the first cycle but magnitudes are different. At the end of the second cycle of shearing, some consolidation continued as shown by points E to G in Fig 12.

The effects of axial shearing can again be observed from the shear transfer-displacement relationship shown in Fig 11. This increase in shear resistance as shown by points E to F and points A to B is a result of consolidation effects. Although the example problem did not address nor demonstrate the effects of cyclic loading, Program CASH is formulated to investigate the shear-transfer characteristic and degradation parameters for such loading.

<u>Extension of the Single-Slice Model to Cyclic Degradation</u>. The framework of Program CASH has been formulated to investigate the soil behavior during pile installation, consolidation and axial loading. As discussed earlier, the ultimate objective is to use the program to understand the shear behavior so as to provide improved procedure to formulate soil support (t-z) curves for a complete soil-pile interaction model such as the one used in the DRIVE program.

As reported by Bogard and Matlock (Ref 1), Schofield and Wroth (Ref 14) and Taylor (Ref 16), the induced shear stress during axial pile loading results in failure occurring on a cylindrical surface a small distance away from the pile wall. The post-failure deformation is then limited to differential slip along this cylindrical shear zone. Under cyclic loading, this continuous slippage gradually degrades the shear resistance of the soil. Matlock, Bogard and Cheang (Ref 11) also monitored the pore pressure variation at the pile wall during cyclic loading. Both increases and decreases of pore water were recorded at that location. Interpretations suggested the possible importance of moisture migrations into and out of the thin shear zone during dilation and compaction of the sheared soil.

As discussed earlier and presented in Fig 8, various static or cyclic volume changes such as compaction, dilation and grain crushing as well as fluid movement can be studied in Program CASH. Through proper guidance and correlation with valid pile load test data, it is expected that the shear-zone behavior including cyclic degradation can be interpreted more accurately.

Summary

To advance the solution of the axial pile problem, a coordinated theoretical and experimental research program has been initiated and is currently underway. The theoretical development involves the formulation of an analytical procedure to study pile-soil interaction during installation, lateral consolidation and subsequent axial loading. Special emphasis is placed on modelling the soil behavior close to the pile wall during cyclic loading.

A computer program CASH was formulated for this study. The simultaneous treatment of pore fluid and soil skeleton in the two-phase soil model has proved to be successful. The addition of simultaneous axial shearing to the cavity expansion and consolidation solution provides a tool for better understanding of axial pile side-friction characteristics such as the state of stress near the pile wall and cyclic degradation effects.

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