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General report/Discussion session 17: Reinforced soil slopes and walls

Soil-reinforcement

Rapport de spécialistes/Séance de discussion 17: Murs et pentes en sols renforcés – Renforcement des sols

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INTRODUCTION

Soil improvement techniques of varying sophistication have been used throughout the history of mankind. The introduction of heavy machinery into earthwork construction during the early parts of this century led to the development of new, more efficient placement and soil improvement techniques.

One such improvement technique introduced during the last half of the century is the strengthening of soils by the insertion of reinforcing elements in either in situ soils or during the construction of soil structures. Elements such as metal strips, geosynthetics, micro piles of various types, and elements developed in situ by the addition and mixing of chemicals with a portion of foundation soils have been successfully used for reinforcement. The last two decades have seen a phenomenal increase in the use of these techniques. A cursory review of the literature shows the coming of a new era in soil reinforcement with the introduction of reinforced earth by Henrie Vidal in 1966.

Papers presented at this meeting reflect widespread acceptance of many of the reinforcing techniques as well as give indications that these methods are reaching a level of maturity as viable geotechnical tools.

A review, for example, of the (the beginning of Vidal era) proceedings VII ICSMFE (1969) show 26 papers on "Natural Slopes and Embankments". None, however, on reinforced soils. About twenty years after Vidal the XI ICSMFE (1984) proceedings contain 10 papers on soil reinforcement. The proceeding of this conference (XII - ICSMFE) will contain in excess of thirty-two papers from eighteen different countries.

Types of papers presented cover review of analysis of historical structures (1)*, laboratory studies and model test (5), large scale and prototype tests (8), behavior of working structures (5), analytical studies (5) and several innovative techniques (5).

Reinforcement materials and types discussed in papers presented range from metal strips, to geosynthetics, corrugated metal sheets, flat stone slabs, micro piles, full scale piles, waste plastic, chemically stabilized soil pilesto anchors.

*Numbers in parenthesis show the number of papers reviewed in each category.

CONTRIBUTIONS TO THIS CONFERENCE

Historical:

An important lesson geotechnical engineers have learned through experience is that the complex nature of soils makes experimentation the foundation for proper design and viable theory.

Historical structures built long before the birth of geotechnology are living proof of the success of the experimentalist. Maldonado Gonzales analyzes the vertical walls of Sierra Nevada at the pre-Columbian city of Tairona. Pre-Columbians, apparently, experimentally determined the phenomenon of soil-reinforcement interaction and used that knowledge to build near-vertical walls.

Laboratory and Model Test:

The need to determine soil-reinforcement interaction to establish design criteria is well recognized in laboratory and field experimentations conducted by the authors of various papers submitted.

It is, at times, difficult however to relate the results of some of the experimental work to reality or to theoretical considerations for reinforced soil structures.

Pull-out boxes of all dimensions have been used by researchers. Boundary effects are often exhibited in some of the results. Furthermore, the apparent lack of the use of a rationally designed or standardized pull-out box makes it difficult to compare results of various workers in this field. I challenge the reinforcement research community to develop a pull-out device which minimizes boundary effects and produces results and lends itself to comparison with results of others. I will look forward to XIII ICSMFE to hear the results of such efforts!

Modeling of soil structures has always been a complex problem. One can never satisfy all similitude rules. Modeling of reinforced soil structures become more perplexing because of difficulties presented by the problem of modeling, particularly, geosynthetic inclusions. Tatsuoka et al, for example, present results of their model studies of geosynthetic reinforced walls. Their study uses cohesive, compressible soils and a modeled geogrid made of thin bronze strips. The relationship of a bronze grid to actual polymeric geogrid is not clear from the paper. The thrust of their study is to verify their assumption that the use of a rigid facing increases the stability of a geogrid reinforced

wall. The study admittedly violates many modeling principles. Problems associated with settlement of the reinforced wall vis-a-vis rigid facing are addressed and a solution is proposed by the authors. The authors suggest that when rigid facing is used a temporary facing such as gabions can be utilized until the settlement of the reinforced wall is completed. The practicability of such an approach may be limited when one considers that foundation soils may settle for a long period of time. The role of a rigid facing in the development of internal stability of a properly designed reinforced soil wall has not been discussed. The authors, however, present a thought provoking concept.

Johnston and Romstat in their thorough study of boundary effects and dilation in pull-out tests show that boundary problems are exhibited even in large pull-out boxes which are not quite yet completely understood. These problems exhibit themselves by reducing the applied overburden pressure, in this case by 35%, due to skin friction developed between the walls of the box and the soil. They also show that the rigid face of the pull-out box presents serious boundary problems and needs further study. It is not shown in the paper whether the authors used a "sleeve" to separate the reinforcing element, near the facing, from the soil to reduce these end effects. This work and similar studies should help us reach our goal of developing a pull-out box with fewer boundary condition problems.

Prestressing of geotextiles used for reinforcement of granular materials may appear to present many advantages. Gorle and Thijs, however, show in their work that prestressing does not provide substantial, therefore economically justifiable benefits. Especially when one considers the relatively high creep potential of geosynthetics, and difficulties associated with prestressing geotextiles having massive dimensions, with today's technology, their conclusions become stronger.

One of the very few papers dealing with reinforcement of clayey soils uses standard undrained triaxial specimens (3.81 cm in diam. x 7.62 cm high) reinforced with geotextile discs and compacted by thumb. The compaction method certainly raises questions about the uniformity of specimens prepared at saturation moistures. Rao and Gupta also conduct pull-out tests in a 6 x 6 cm device. The experimental errors presented by these testing methods appear to be unsurmountable and difficult to estimate.

Pang conducts a series of model experiments of a retaining structure, he has named soil/caisson buttress, used in Hong Kong. The experiments are conducted in a 50 cm. x 48 cm. x 40 cm. box. He concludes that limit equilibrium analysis for such structures is conservative but could be used for design.

Large Scale & Prototype Test:

Large scale model experiments on geogrid reinforced soil walls are conducted by Bathurst and Benjamin. Their work provides significant insight for the failure mechanism of walls reinforced with geosynthetics.

Experiments conducted on instrumented reinforced walls 3 meters high, 2.4 meters wide point out some of the pitfalls of relating failure to the behavior of the wall at working stresses. It raises the question whether it is

appropriate to use a safety factor based on limiting equilibrium approach.

They report observing two failure mechanisms; one "soil-to-soil failure through, reinforced mass" followed by rupture of the grids starting from the bottom layer progressing towards the top. Strain levels of about 1% during the construction of the wall and about 9% at failure were recorded.

Results clearly show the time dependant deformation (creep) of the geogrid with the addition of surcharge loads and demonstrate the importance of considering such deformations in geosynthetic reinforcement.

The authors do not counter any significant stresses in the reinforcement at embedment lengths of 0.5 to 0.7 times the height of the wall. The experiments indicate that connection loads at wall facings, and at failure reach peak loads equivalent to those in the reinforcement at the location of the failure surface.

The behavior of a prototype embankment reinforced with metal strips is reported by Naresh et al. The results appear to be influenced by construction procedures. Deformation of skin elements in the order of 2% to 2.5% were measured during the construction and loading of the wall respectively.

In general, reinforced soil walls are built with cohesionless soils because of problems associated with developing satisfactory soil/reinforcement interaction in saturated clays or clayey soils in the presence of excess hydrostatic pore pressures. The solution of this problem would open an entirely new horizon for the geotechnical engineer faced with the lack of easily accessible sources of cohesionless materials.

Fourie and Fabian report their efforts in establishing failure mechanisms and soil-geotextile interaction behavior in reinforced clay walls using non-woven geotextiles. Undrained pull out tests performed with woven and non-woven geotextiles as well as with geogrids show that non-woven geotextiles develop the highest degree of pull out resistance followed by that developed by woven fabrics. Geogrids appear to perform poorly in that environment. Authors relate the better performance of the non-woven fabric to its transmittivity. Their results indeed show that in large scale tests there is settlement of the reinforced wall taking place, thus some drainage through the non-woven geotextile is taking place resulting in consolidation of the soils at the soil-geotextile interface.

The authors do not address the possible interlocking, or foot printing, that might be developing between soil, particularly silt, particles and the geotextiles. Under undrained conditions such action may be just as important as the partial mobilization of the soil-geosynthetic interaction. The strains observed in the geotextiles as a result of the surcharging are less than 10% with no evidence of pull out. The authors conclude that even though significantly higher loads are carried by the reinforced wall indicating that the non-woven reinforcement was partially effective, the full geotextile-soil interaction did not develop in these practically undrained tests.

Experiments on three soil nailing projects at different sites shed further light on the behavior of nailed walls in the paper presented by Plumelle, et al.

The results of these full scale tests show

that nails in general work in tension, however, they may be placed in a flexural mode immediately prior to failure. One of the important conclusions reached by observing experiments performed at different sites with differing construction techniques is that the degree of effectiveness of nails depend on construction methods. Thus it emphasizes the presence of a sometimes ignored parameter in earthwork design and construction. They show that at failure nailed soils moved as rigid masses, and maximum tension in the nailed soil mass occurred at the interface of the active and passive zones near the rear of the nailed mass.

Hettler and Schwing recognizing the vagaries of soil-nail interaction as also shown by Plumelle et al propose a stochastic approach for determining the numerical value of nail/soil friction. Their results show that it is possible to define a reasonably reliable, mean value by using a stochastic approach. However, they caution the reader that the coefficient of variation depends on soil and construction methods among other factors. The development and use of a global coefficient of variation does not appear to be within reach.

Temporal and his co-workers present extensive, large scale test results on reinforced or anchored soils. In recognition of the need to use locally available soils, they have constructed full scale walls using sandy clays, silty clays and granular fill. Their work shows the need for exercising quality control on compaction and moisture content of particularly cohesive materials. Where reinforced earth construction does not appear feasible the NEW anchored earth method developed by Brandl and Dalmatiner (1986) provides an economical solution. The authors also discuss the durability of reinforcing elements in various soil environments they encountered, and they conclude that non-metallic elements and anchors are desirable alternatives to metallic ones.

Their attempts to relate the ultimate load capacity of the NEW anchored wall system to undrained or drained shear strength of the soil points out the need for the development of analytical methods which closely model the anchor, anchor strap and the soil. I expect that their continuing work with full scale models will be very productive in answering some of the questions concerning design and construction.

Load testing of a full scale (4.8 m. high x 20 m. long) embankment slope reinforced with geosynthetics to failure to verify design procedures is described by Fannin and Hermann. Their work further explains the behavior of such structures and reinforces both theoretical and analytical works of others who accept the limit equilibrium approach for design. Their instrumentation which appears to have survived for at least the six month period reported produce distribution of stresses in the various layers of reinforcement as well as strains in these layers. Their measurements show the mobilization of larger forces in the middle layers of reinforcement and smaller ones in the base layer of the slope. There appears to be uniform load transfer in all but the base layer of reinforcement. The response of the base layer to loading is somewhat lagging behind those of layers above. Perhaps because the time dependency of elongation of geosynthetics delay the mobilization of the load transfer to lower layers or because of boundary effects. This

study, again, verifies that closer vertical spacing of reinforcement at the base of the slope results in more uniform load distribution.

Measured strains in the reinforcement near the face of the slope are in the vicinity of 0.6% decreasing to insignificant intensities towards the fixed end of the reinforcement. The design procedures of Jewell et al (1984) predict the behavior of this structure under load accurately. Back calculations show the propriety of using plane strain angle of friction from direct shear tests for design. The author's work provide a strong link between theory and application.

In quest of evolving more economical designs for reinforced earth walls Bastick et al study the behavior of a reinforced earth wall (Terre Armee) with short (0.4 to 0.5 x the height of the wall) reinforcing elements.

Their well instrumented and monitored experimental "short" (short refers to the length of the reinforcement) walls (10.5 m. high x 45 m. long) show that the plane of maximum stress in the reinforcement is practically identical to those observed on "long" (0.7 or longer x height) reinforcing elements. The location of the plane of maximum stress is measured to be slightly closer to the facing than the location of the same in walls reinforced with longer elements. The reduction of the length of the elements appear to uniquely affect the zone in which the average mobilized friction along the reinforcing elements should be higher. The pressure at the base of the wall attains its maximum value away from the facing, developing lower values of pressure near the facing. The authors explain this occurrence as resulting from the fact that part of the vertical load is carried by the reinforcement. It is also conceivable that the compaction of the embankment behind the reinforced mass may have caused vertical pressures causing a shifting of pressures at the base.

A detailed numerical analysis of the global equilibrium of each wall tested shows that the force behind the wall is highly inclined towards the base. This effect reduces the overturning moment which in "short" walls is of particular importance.

Working Structures: (Case Histories)

The versatility and the applicability of reinforced soil designs to ostensibly impossible situations are well illustrated by the documentation of case histories of working structures (opposed to experimental structures) presented in this conference.

In reviewing these cases one must not only pause and acknowledge the skill of the designers and builders but must also recognize the creativity and tenacity of a young and dynamic geosynthetics industry who continues to enhance and produce materials which are becoming increasingly capable of solving the problems of men and resisting the destructive forces of nature.

A complex and major slope stability problem is resolved by the use of geosynthetic (grid) reinforced buttress by Bonaparte et al. A 34 m. high reinforced buttress is designed, built and instrumented, to improve the stability of a natural slope of a hillside residential subdivision in development stage. Various

alternatives to ameliorate the stability of the subject slope were reviewed and rejected for reasons of economics and impracticability except the use of a reinforced soil buttress.

The authors use Bishop's (1955) modified method of slices to determine the internal stability of 1.5. This analysis results in a design requiring the use of 48 layers of reinforcement with variable spacing of 0.3 to 1.8 m. The external stability analysis is performed following both Spencer's (1967) and Janbu's (1973) stability analysis.

Inclinometers show horizontal movements of 8 to 12 mm. at the base of the buttress mostly occurring during the construction. Only about 5 mm. of horizontal post-construction deformation is observed. Strain gages placed on geogrids measure maximum strains of 0.4% with the average being around 0.2%. Vertical settlements of 3 to 18 mm. (measured at the top of the buttress) are experienced during construction. These measurements verify the validity of computed safety factors and show the suitability of the design and construction methodologies to the solution of this problem.

Rimoldi and co-authors expound the use of another geosynthetic (geogrid) reinforced slope to solve a very difficult design and construction problem. They were faced with the design of a near vertical (70°), 13 m. high, wall to meet aesthetic requirements of an elaborate landscaping scheme at a site with a history of a slope failure. The slope was to be designed incorporating various large and small, concave and convex curvatures. A 13 m. high portion of the slope was to have a waterfall with potential of water infiltration and imposition of a large surcharge load (70 km/m²). The finished slope was, also, to be subjected to 1250 mm./yr of irrigation and nitrate fertilizer. The construction site was classified to be in zone II seismic loads (0.1 g to 0.15 g.).

The slope stabilization methods considered by the designers range from conventional gravity retaining walls, cribblock walls to various reinforced soil walls. Economical considerations focus the design on the use of reinforced soil walls. The presence of irrigation water and the planned use of chemical fertilizers result in the elimination of the use of metal reinforcement to avoid corrosion problems. A high density polyethylene (HDPE) grid is chosen for reinforcing elements.

Internal (Jewell et al 1984) and external (Bishop 1955) stability analysis performed by the authors is augmented with considerations of seismic factors. The convex and concave curves of the reinforced wall are treated as arches transforming portion of the radial forces into tangential forces. A free draining backfill material is specified.

Geocomposite drains are provided for the drainage of vegetative cells. Unbonded, reinforced concrete blocks are used for the facing. The project is successfully constructed thanks to technology and materials developed in the last three decades.

Munfakh discusses the design, construction and competitive bidding aspects of reinforced soil structures in his presentation of three case histories.

The problem of providing a temporary access road to a tunnel portal construction in a remote and rugged terrain is found to require the construction of a 8 m. high, 2,400 m. long

retaining wall with a minimum service life of 10 yrs. Three different types of walls, gabion, reinforced earth, and geotextile reinforced, were designed. Potential builders are provided with all three designs for bidding purposes. The results show the average cost of geotextile to be 32% less than reinforced earth and 42% less than gabion. The geotextile reinforced wall is constructed by wrapping the face of the slope with the reinforcing geotextile element and a wire mesh gunite concrete cover.

In the second project discussed by Munfakh the construction of a 63 m. long and 11 m. high retaining wall is necessitated along a roadway to provide a buffer zone and a holding platform for small, fallen rocks in a rock slide region.

The walls initially considered for design and construction are a gravity type concrete retaining wall a concrete faced tieback wall and reinforced earth wall. After due consideration of the economics and the construction for each alternative the reinforced earth wall is selected for use. The construction is completed in about two months.

The third problem discussed by Munfakh is the selection of a construction method for a major highway ramp. In this case three alternatives are studied; building the ramp by driving sheet piling, reinforced concrete wall, and a nailed soil wall. The nailed soil method is selected. He reports that in the design of all three walls the external stability governed the selection of reinforcing elements. This paper illustrates the benefits of reinforced soil structures over more conventional ones, as well as discusses the pragmatic considerations such as comparative cost, competitive bidding, and construction time.

The reinforcement of an excavated slope with nails to facilitate the construction of the basement floors of a large building is discussed by Cardoso and Carreto. The authors conduct full scale pull-out tests prior to the construction in addition to a series of geotechnical investigations. They use two and three dimensional FEM to determine the behavior of the excavated slope. Cardoso and Carreto emphasize the dependency of the soil modulus (for FEM) on the stress path of the excavated sections. The limitation of FEM to model excavations properly because of the difficulty presented by the selection of the proper modulus appears to be exhibited in their results where a plot of displacement versus progress of the excavation show that predicted horizontal displacement depart from the measured ones as the excavation proceeds. These measurements also show that the three dimensional analysis may be more suitable to model the case. Nevertheless both 2D and 3D results show serious limitations. The authors conclude that nailing is effective in maintaining the horizontal movements associated with excavations to a minimum.

Murray et al have conducted a survey in England and France to determine the use of reinforced soil in areas subject to subsidence resulting from mining operations. Their work concludes that there are not many cases which are well documented or widely reported. However, the cases where they have been able to identify and analyze, the use of reinforced soil in mining subsidence areas has been very successful in the solution of this problem. Their analysis indicates that where subsidence occurs horizontal strains also occur which may apply compressive stresses to reinforcing

elements, partially overcoming the tensile stresses within it. They point out, however, that in such areas if tensile stresses were to develop due to strains then the tensile stress in the reinforcing element may exceed the tensile stresses produced by the weight of the structure which in turn may fully mobilize the interface shear strength causing slippage. In their analysis they apply FEM to determine the behavior of reinforced soils above subsidence areas. Their analysis points out the vulnerability of FEM as a reinforced soil modeling tool and emphasizes the need for better, more realistic, modeling tools.

Analytical Studies:

Design of walls reinforced with, particularly, geosynthetics recognize the presence of deformations due to shear displacement and creep of reinforcing elements. They often do not, however, provide a practical and logical means of determining vertical and horizontal deformation of reinforced walls. Jewell and Milligan's contribution to this conference addresses this need and furnishes a practical approach. The authors analyze displacement of reinforced walls in relation to an idealized equilibrium state of stress. While doing so they assume that stress characteristics are as critical as velocity characteristics behind a retaining wall. They, therefore, reason that reinforcement should "provide equilibrium for both".

Authors analyze ideal vertical spacing versus uniform spacing schemes for reinforcing elements, as well as ideal length and truncated length of reinforcement in relation to vertical and horizontal movements. They summarize their results in four sets of very useful charts from where one can obtain vertical and horizontal displacements for various lengths and spacing combinations of reinforcement.

Anthoine and Salencon describe the principles of a kinematic limit analysis approach for iterative design of reinforced soil structures using an interactive computer program (STARS). The yield criterion of the reinforcement allows consideration of a generalized state of stress (tension, shear, bending) and a perfect adherence is assumed to prevail at the interfaces. Considering a rigid body motion of the active zone, the kinematically admissible failure mechanisms can be either translational or rotational. The active zone is assumed to be separated from the resistant zone either by a surface of discontinuity in the velocity field or by a transition zone where the velocity decreases linearly with the rotational radius. This latter assumption allows a significant improvement of the estimation of the safety factor for reinforced soil systems where the limit forces in the reinforcements do not depend only upon the normal interface stress. The authors illustrate the use of their method in design optimization of a vertical wall retained by one layer of reinforcement. This method, however, has some limitations: (1) The assumption of perfect interface adherence is too restrictive. (2) Typically in limit analysis only limit forces are considered but no consideration is given to constitutive equations of the reinforcement and the soil. Specifically, no consideration is given to the extensibility (creep) of the reinforcement which

significantly affects the behavior of reinforced soil structures. (3) The method yields only a global safety factor assumed to be constant along the potential sliding surface or shear zone, while the failure mechanism in reinforced soil structures is progressive. (4) The method does not yield an estimate of the working stresses in the reinforcements under the anticipated working loads.

The treatment of reinforced soil as a homogenized anisotropic medium is suggested by de Buhan. He indicates that homogenization approach can be efficiently used to search for both kinematically and statically admissible solutions for the design of reinforced soil structures. The author illustrates the use of this approach in design optimization of a vertical reinforced earth wall with uniform surface loading. The design scheme is optimized through the search for a reinforcement distribution function which maximizes the bearing capacity of the structure, considering a translational failure mechanism. However, for the assumed kinematics of translational failure mechanism, the solution is only the function of the sum of resisting forces and not their distribution. The selected design example does not appear to be appropriate for the purpose of illustrating the role of the reinforcement distribution in the stability analysis. The solution derived by the author is identical to the classical kinematically and statically admissible solutions for earth retaining walls and does not integrate any consideration of the reinforcement effect on the velocity field in reinforced soil structures. The results appear to be in conflict with significant data base and previous theoretical analyses of the behavior of reinforced earth structures.

The application of Janbu's method of slope stability analysis to reinforced slopes is discussed by Vanicek & Skopek. They illustrate that this method can be successfully applied to geosynthetic reinforced slopes. They propose the use of a very low ratio (equal to or less than 0.25) of design tensile to ultimate tensile strength of geosynthetic to eliminate the effect of creep which appears to be too conservative. They also recommend reinforcement spacings equivalent to 1/6 to 1/16 of the height of the reinforced embankment.

Matsui and San propose a new procedure for slope stability analysis of reinforced slopes in cuts based upon the use of finite element method to evaluate 1) the local safety factor along the potential failure surface and 2) the occurrence of a shear failure as the shear strain level along the potential slip line exceeds the failure shear strain. The occurrence of a shear failure is defined by the development of a shear failure zone from the toe to the crest of the slope, and characterized by a critical safety factor with respect to the soil strength, termed the critical shear strength reduction ratio. The global stability of the reinforced slope along the critical surface is then evaluated using the limit equilibrium method.

Finite element analysis (F.E.M.) for simulation of the construction process assumes elastic (non-linear) soil and (linear) soft rocks and uses elastoplastic joint elements to simulate slippage at the interfaces (soil-reinforcement or soil rock). The reinforcement is assumed to be linearly elastic. A full scale experiment on a cut slope reinforced by root

piles provides the data base to evaluate the F.E.M. and the proposed slope stability analysis procedure.

The authors illustrate that F.E.M. predictions substantially agree with measured forces in the reinforcements, indicating maximum tensile forces nearby the anchoring points in the soft rock at the rear of the reinforcements. The numerical simulations illustrated that reinforcement decreases the shear strain and increases the safety factors. Location of critical failure surfaces and corresponding values of the safety factors predicted by the F.E.M. corresponds fairly well to those obtained using a conventional slice method. The predicted failure surface of the reinforced slope is quite close to the locus of the maximum tensile forces. In light of these results the authors conclude that their proposed design procedure is applicable to similar cases.

There are, however, inherent difficulties in modeling soil response to unloading stress path induced by excavation, it has long been recognized that elastic models cannot be used to adequately model soil response to unloading, furthermore, modeling large strains in soil (up to failure shear strain) cannot be adequately done using elastic models.

Three dimensional aspects of soil-reinforcement interaction are difficult to simulate, the soil reinforcement interaction is highly dependent upon the soil dilatancy which is not included in the elastic soil model. There, also, are difficulties to obtain relevant design parameters specifically for the joint elements.

Application of F.E.M. is limited by the inherent vicissitude of modelling assumption but also by the limited precision of the design parameters.

The methodology presented by the authors is of particular interest for a parametric study on the effect of the design parameters on the reinforcement efficiency and local or global structure stability. As such it provides a useful design tool for difficult design cases such as with complex geometry or stratified soil.

Innovations:

Texsol is an innovative soil reinforcement method developed during the last decade. Texsol is formed by mixing sand and continuous synthetic filaments using especially designed equipment. This equipment mixes and delivers the product for placement. The presence of the continuous filament impacts cohesion to the mixture thus rendering it stable against static and dynamic loads. Gigan et al provide results of their ongoing studies on full scale Texsol slopes.

They have tested two identical Texsol slopes by loading them until failure to determine, among other factors, the influence of the placement angle of Texsol with the shear angle. In both cases failure occurs by rotation and by punching.

For steep slopes they propose the use of a design method based on punching shear resistance which takes into account the anisotropy of Texsol. For walls having slopes of less than 60° with the horizontal their computations indicate that failure occurs by sliding along a non-circular phase.

They show that anisotropy of this material has to take into account in the design and placement.

Gielly et al have applied earth reinforcement techniques to solving two problems; slope stability and recycling of waste plastics. The Plasterre process they introduce utilizes waste polyethylene and polypropylene bottles and film as reinforcement elements. About 5% by weight of (the soil) waste synthetics is placed in a reinforcement layer in a manner that it assures continuity by overlapping of the pieces. Each layer, similar to reinforced soil construction is covered with soil which is then compacted.

An experimental embankment having a 55% slope has been successfully constructed. This ingenious process promises to help the geotechnical engineers to provide a solution to an environmental problem: the reuse of non-returnable synthetic products. However, one must know more about the durability of these products before placing them in semi-permanent structures as reinforcement. The non-returnable synthetic materials may not have proper treatment against thermal oxidation or other natural processes which may degrade these elements. Nevertheless, I am sure that the development of Plasterre process will be watched with interest.

A novel concept for the design and construction of a retaining wall is advanced by Morin and Curt.

A wall named Ter-voile by the authors is built by erecting a series of U - Shaped corrugated, galvanized metal sections vertically with the open end of the "U" facing the inside of the retaining structure.

The wings of these containment elements extend into the fill. The elements are riveted or bolted to each other and filled with granular materials. The exterior of the "U" forms the facing of the wall. The stability of this structure is assumed to be governed by internal and external stabilities. The internal stability is controlled by the coefficient of friction between the soil and the metal units and the horizontal resistance developed between the embedded portions of the metal elements (on the two sides of the wall) and the embankment soil. The internal stability of the structure depends on the properties of the material forming the U shaped (voile) screens and the rivets or bolts used to attach the screens to each other. The external stability of the wall is governed by factors similar to those used for other retaining structures. Morin and Curt have constructed a full scale experimental wall 22.5 m. long and 5 m. high with a 4 m. embedment. Nine cells are used for this experimental wall. The thickness of the screen at the wall facing is 2 mm. and that of the embedded parts are 2.8 mm. A granular fill is placed inside these cells and compacted to 92% modified procter density. Parallel to this the authors performed direct shear tests to determine the angle of internal friction of the fill material as well as the friction angle between metal elements and the soil. The wall is instrumented and observed for 180 days. During the observation period the center three cells are surcharged. The results indicated that the displacement of the wall is inconsequential especially after construction is completed. Surcharging produces only 3 mm. of horizontal displacement of the wall facing. This structure could not be failed under surcharge. The K under surcharge approached K_0 .

As a result of these and laboratory model studies it is concluded that the encapsulated soil is overconsolidated by compaction. An average value of 0.39 is accepted for "K". During winter months the K value increases because of expansion resulting from the penetration of frost into the structure. The tests also show that for certain shapes the wall acts as a conventional gravity wall. This simple and new concept present new opportunities for the geotechnical researcher and designer.

Lippoman and Gudehus provide us with a new method to solve the problems presented by the movements resulting from creep in slopes; the use of reinforced concrete piles driven through the plane of potential failure (or movement) of the slope into competent soils. The piles called dowels provide shear resistance along the weakened creep surface and reduce the movement of the slope to tolerable levels.

Mixed in-plane stabilized soil columns could be very effective in reinforcing embankment foundations, light building foundations and slopes. One of the reasons, however, that they are not commonly utilized is the fear that good quality control procedures for the formed column do not exist (except excavating or loading of test columns) which raises concern about the continuity of the columns formed by conventional methods. Cartier et al describe the COL-MIX method of in-plane mixing which is accomplished by the use of a machine incorporating dual helical augers operated by two independent motors. The augers turn in opposite directions and they can be reversed independently. The equipment initially breaks up the cohesive soil by augering and by introducing lime into the soil. It also homogenizes the soil-additive (lime, portland cement or a combination) system and densifies the mixed column in place. This concept and the new equipment eliminates non-uniformities in material along the length of the column, thus overcoming one of the most serious objections to the use of in-situ stabilized columns.

A system of waffled panels held in place by open end pipe anchorage is introduced by Ledeuil et al. The Geosell-Geotool system (both registered trademarks) is used to provide a waterproof facing with built in drains to facilitate the removal of water from behind the wall. The Geosell-Geotool system appears to have potential for application to a wide variety of structures ranging from swimming pools to noise barriers for roads.

SUMMARY

A review of papers contributed to XII ICSMFE clearly show that soil reinforcement during the last few years have reached a new level of intellectual and technical maturity. It is gratifying to see that the research community, by-and-large, has recognized the pragmatic needs of the practitioner in the development of improved or new design methods.

Efforts are continuing to study structures built in earlier years to learn from their success and failures. Existing analytical methods are being continuously challenged and scrutinized to reach perfection. There still remains a serious need to develop analytical and design methodologies to predict and analyze vertical and horizontal displacements of reinforced walls and slopes. The existing

methods do not allow the incorporation of the effects of compaction and construction techniques in the design of reinforced soil structures. The behavior of fine grained soils in reinforced slopes and walls is neither well understood nor explained by analytical methods.

Modeling of soil is an inherently difficult problem. Modeling of reinforced soil, because of the introduction of another element, becomes more complex. The experimental developments are still suffering from our inability to satisfactorily model soil-reinforcement systems and stress-strain conditions occurring in the field. This appears to be an area which is in great need for further attention and work. The geotechnical engineer needs to pay greater attention to the micro media of soil-reinforcement systems before being able to model the macro media! The soil-reinforcement continuum need to be better understood in its microscopic sense. Perhaps such understanding will lead to the development of new modeling methods and materials, such as a "model" soil made of a molecular structure that mimics the behavior of soil particles under load. Interdisciplinary efforts to review the feasibility of such development is of great importance. Realistic analytical and physical guidelines for modeling should be developed to provide wide acceptance of the result of model experiments.

The development of a standardized pull-out box substantially free of boundary effects should be made a high priority research item. Such development should be verified with full scale pull-out studies.

The continuing efforts of experimentalist in pursuit of answers to practical and theoretical questions are commendable. Without the benefits derived from full scale experiments it would be difficult and inefficient to design safe, economical, reinforced soil structures. The engineer, whenever faced with a substantial or unusual reinforced soil structure should do all to convince the owners to provide funding for instrumentation and observation during at least critical periods. Since geosynthetics engineering is still a young discipline it is important to also provide for long term observations.

Papers reviewed show a developing trend of partnership between owners and geosynthetics manufacturers to provide the means for better understanding the behavior of the soil-reinforcement systems through observations.

Innovations resulting from free thinking, and the entrepreneurial minds of engineers and scientists are continuing to appear in the soil reinforcement discipline. The inventiveness of these individuals, business entities, or government agencies continue to improve the state-of-the-art, the state-of-the-practice, and provide the tools for the geotechnical engineers to serve their fellow man in more efficient and elegant ways.

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