The use of the X-Ray Technique in the Study of Soil-Reinforcement Interaction

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ABSTRACT: There are only a few non-destructive techniques available to observe and quantify the patterns of local deformation of soil masses and the details of soil-reinforcement interaction. Among them the x-ray radiography is a promising tool because it allows to penetrate reinforced geomaterials and to record images of their internal state while minimizing both the disturbance and the boundary effects on the observed mechanism. Moreover, with this technique, it is possible to determine quantitatively the internal state of the composite material, subjected to boundary loads. An experimental study was carried out on a two-layer soil system reinforced at the interface by a geotextile. The experimental setup was conceived to represent a plane strain state of deformation and static loads were applied on the surface of the model by small increments. The x-ray technique was used to observe the field of internal deformation and to analyze the details of the soil-reinforcement mechanism. Small lead shots, embedded in the model, were employed as displacement markers for both the soils and the reinforcing geotextile. The results obtained on both reinforced and unreinforced systems show that the x-ray radiography is a powerful means to be used to improve our understanding of soil-reinforcement interaction.

1. Introduction

It is generally agreed that the inclusion of geotextiles and geogrids in roads, railways and retaining structures, apart from its function of drainage, separation and filtration, does provide a mechanical improvement of the soil behavior.

Unfortunately even if the soil-reinforcement interaction depends mostly upon the relative stiffness of soil and fabric and by the anchorage capacity of the latter [BOURDEAU *et al.*, 1988] there is a lack of detailed and reliable experimental data to assess the relative contribution of these two factors. Because of the complexity of the soil-reinforcement mechanism, it is necessary to visualize and analyze quantitavely the soil-inclusion interaction in scale models in laboratories.

Several non-destructive techniques have been proposed to observe and quantify the patterns of local deformation of reinforced and unreinforced soils. MIURA *et al.* [1990] have proposed the use of miniature strain gauges, directly installed on geosynthetic inclusions to monitor their tensile deformations. However this technique does not provide information on the patterns of deformation in the surrounding soil. Alternatively recourse has been made to photographic techniques which allow to follow the deformation of thin layers of colored soil particles through the transparent boundaries of scale models. These traditional methods combined with stereophotogrammetric techniques [BUTTERFIELD *et al.*, 1970], provide a direct observation of the motion of individual soil particles during the deformation process [DESRUES, 1983]. It should be noted that photographic techniques allow to monitor only the deformation of the material in contact with the boundaries of the scale model. Thus their applicability is greatly affected by side effects.

The use of x-ray radiography can help overcoming these limitations. By using penetrating radiations, images of the internal state of soil-reinforcement systems can be recorded and their deformation determined quantitatively when subjected to boundary loads. After a brief review of soil reinforcing principles, this paper describes the technique of x-ray radiography in soil mechanics and reports its recent application to the study of soil-geotextile interaction.

2. Mechanism of soil-reinforcement interaction

The use of fabrics in geotechnics is based upon the idea of improving the properties of soil, which can resist to compression and shearing, but can hardly resist to tension, by tensile-resistant inclusions. This principle is, in concept similar to that of reinforced concrete.

The mechanical improvement of the soil behavior may be achieved by:

- tridimensional reinforcement which, through the inclusion of fibers in the soil mass, aims to create a homogeneous material whose resistance properties are improved of the same amount in every direction as compared to those of natural soils;
- oriented reinforcement by inclusion of fabric sheets or polymeric grids which improves the soil

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performance in particular directions depending upon the relative orientation of applied loads and fabrics layers.

In the latter case the soil-reinforcement interaction is mainly due to:

- mobilization of interface friction which causes the development of tensile stresses along the geotextile. This type of interaction generates lateral restraint and additional confining stresses in the surrounding soil. In consequence, the stiffness and the bearing capacity of the reinfoced soil layers are increased [MILLIGAN *et al.*, 1986; LOVE *et al.*, 1987];
- membrane tensile forces, developed in the inclusion as a consequence of its deflection. This results in interface contact pressure that provides additional bearing support to the foundation soil under surface applied loading [NIEUWENHUIS, 1977; GIROUD and NOIRAY, 1981; BOURDEAU, 1989]. This principle is illustrated in fig. 1.

The effectiveness of these mechanisms, which may develop separately or simultaneously, depends essentially on the friction available at the soil-fabric interface, the relative stiffness of soil and geotextile and the amount of interface deflection.

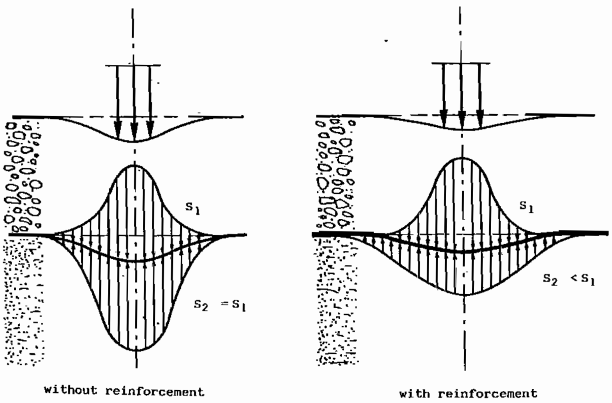

Fig. 1. - Effect of membrane support in a two-layer soil system reinforced at the interface (S1, S2: load induced pressure at the interface).
Effetto di rinforzo a membrana in un terreno e due strati (S1, S2: pressioni indotte alla interfaccia).

3. Experimental method: x-ray imaging of reinforced soils

The radiographic technique uses penetrating radiations, such as x-rays, to take shadow-images of the internal structure of materials. Since the discovery of its principle in 1895, the application of radiography to quantitative analysis in soil engineering has been slow to develop.

The first work in this field was done by GERBER [1929] who used the x-ray radiography to study the internal patterns of deformation in sand. His method consisted of recording pictures of small lead pellets embedded in the soil body. By comparing images taken before and after deformation of the sand, he was able to determine the displacements of the lead pellets supposed to represent those of the surrounding sand grains.

During 30 years this pionner's work was followed by only a few applications. In the 60's a systematic development of the method for the study of plane strain scale models was undertaken in Cambridge University [ROSCOE *et al.*, 1963; ARTHUR *et al.*, 1964; ARTHUR *et al.*, 1965]. Attempts were made in these studies to account for the mechanical and geometrical errors involved in the method and to implement the numerical processing of the information. Further progress in the equipment available and more recent research work have demonstrated the potential of the x-ray imaging in the quantitative analysis of the local deformation of geomaterials when this technique is used in association with computerized image analysis and data processing [BALASUBRAMANIAM, 1974, 1976; WOLFERTS, 1975; SCHWAB *et al.*, 1977; TAKAGI *et al.*, 1983; KIMURA *et al.*, 1985].

The same methodology was applied to study the deformation of loose cohesionless soils under applied surface loads [BOURDEAU, 1986; BOURDEAU and RECORDON, 1988, 1989]. The processing of radiographic pictures involved the determination of the coordinates of almost 300 lead shot markers for each one, the computation of their dispacements and the derivation of the local strains. Optimal reduction of parallax and other measurement errors was achieved by applying the Helmert geometric transform to the set of recorded coordinates, similarly to the technique used in photogrammetry [BOURDEAU, 1980]. The resulting measurement accuracy was of the order of 50 microns for the displacements and 0.2% for the strains.

Therefore there is experimental evidence that x-ray imaging can provide the means to determine with accuracy the deformation field of laboratory scale models of soil systems while minimizing both disturbance and boundary effects.

4. X-ray observation of a two-layer soil system reinforced at the interface

4.1. *Experimental program*

An experimental investigation was carried on at the Ecole Polytechnique Fédérale in Lausanne to study the mechanism of reinforcement by geotextile fabrics in a two-layer soil system under applied surface loading [BOURDEAU and PARDI, 1989]. The geometry of the scale model and the characteristics of the apparatus are illustrated in figs. 2 and 3. A container with smooth rigid walls was used to simulate a plane strain state of deformation. Static loads were applied by small increments through a rigid rough plate at the surface of the model. The model consisted of a subgrade layer of silt and an upper layer of clean uniformly graded sand, separated by a woven polyester geotextile. Both the soil materials were dry and placed in a loose state. The materials properties are summarized in tab. 1 while the main characteristics of the x-ray equipment and radiographic parameters are reported in tab. 2.

Small lead shots (2 mm in diameter) were used as displacement markers for both the soils and the geotextile. A radiography of the model was taken after each load increment and compared to the image of the initial state. This allowed to determine the patterns of internal deformation of the soil and the local elongation of the geotextile. Knowing the tensile modulus of the fabric, it is possible to derive from these measurements the corresponding values of tension along the inclusion.

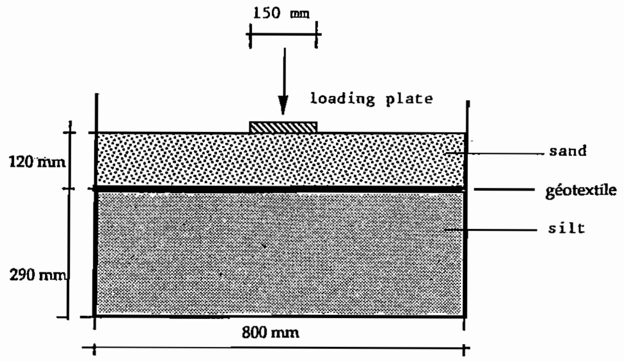

Fig. 2. - Geometry and dimensions of the scale model tested.
Geometria e dimensioni del modello.

Tabella 1. - *Material data (Caratteristiche dei materiali)*

	Sand	Silt
Average particle size (mm)	0.3	0.04
Dry unit weight (kN/m^3)	15.5	12.1
Average porosity	0.40	0.575
Water content (%)	0	0
Cohesion (Kpa)	0	0
Angle of internal friction	34	30

	woven geotextile
Composition	Polyester/Polyamide
Tensile strenght	230 kN/m at 10% strain
Tensile modulus	2600 kN at 10% of failure load

Table 2. - *Radiographic data (Dati radiografici)*

X-ray tube	Philips MG150
X-ray source	Beryllium 3×3 mm
Soil thickness	160 mm
Glass walss	30 mm
Source-film distance	600 mm
Film	Kodak Industrex AX
Exposure paramenters	6 minutes under 120 kV and 28 mA

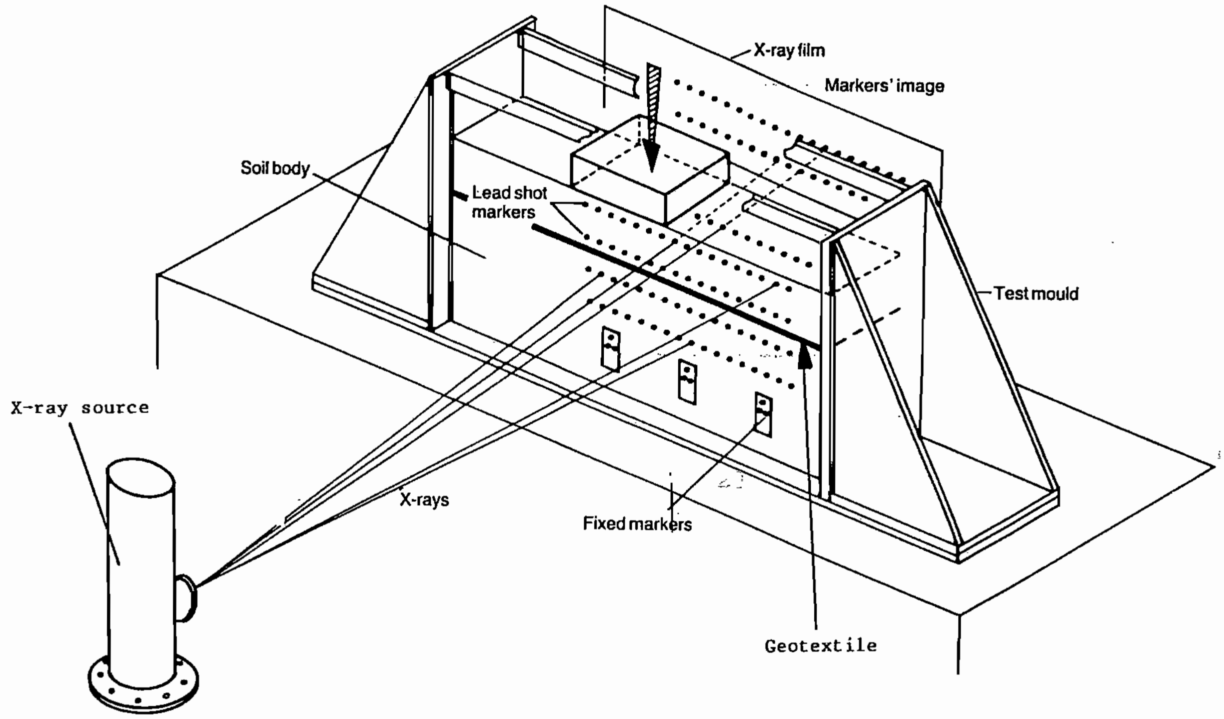

Fig. 3. - Principle of plane strain loading with x-ray measurements of displacement patterns.
Sistema di carico e misure radiografiche degli spostamenti.

The radiographic images were processed according to the numerical technique outlined in the previous section [BOURDEAU, 1986]. Experiments were carried out on the reinforced system while a test without geotextile was used as a comparison. The results of the study are discussed in the following sections.

4.2 *Observed mechanism of deformation*

In fig. 4 the plate load-settlement curve without geotextile is compared to that obtained with a woven geotextile. There is a significant improvement in the load-settlement response of the system in presence of reinforcement. In both cases the model has been subjected to an unloading cycle which shows that settlements are unreversible upon unloading.

The patterns of internal deformation for the two-layer system without inclusion are representend in fig. 5 (cumulative displacement vectors for a 93 kPa applied pressure) and in fig. 6 (incremental displacement vectors corresponding to an increase in the applied pressure from 93 kPa to 124 kPa); they are typical of the response of dry loose cohesionless soils under applied surface load with low overburden pressure. Note the different scales chosen to represent distances and displacments.

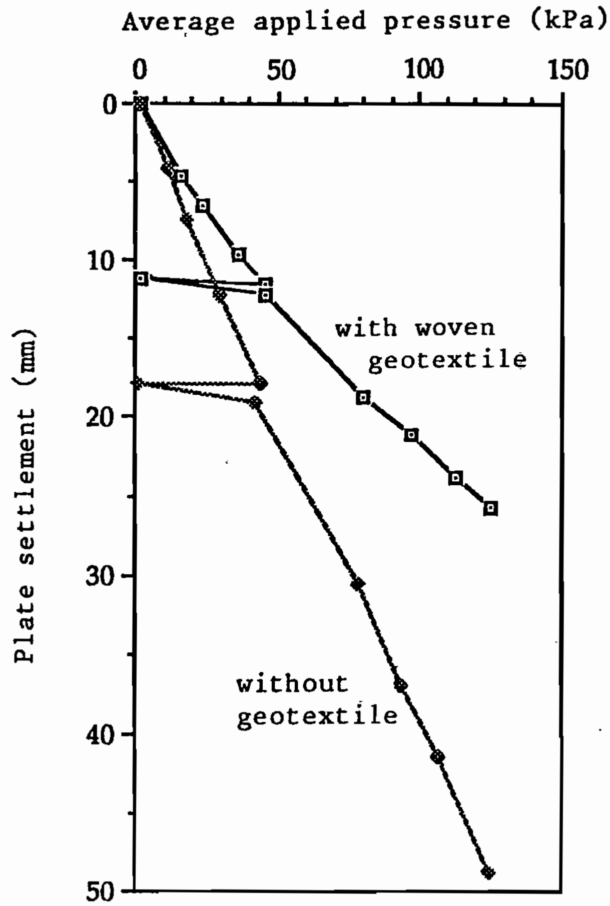

Fig. 4. - Load-settlement responses of the reinforced and unreinforced two-layer soil system.
Andamento carichi-cedimenti del sistema rinforzato e non rinforzato.

Fig. 5 shows the deformation mechanism of the unreinforced model consisting of a general settlement in both layers combined with lateral spreading of the two soils outside the loaded area and an increase of the state of compaction of the silt foundation layer.

The continuity of the displacements at the interface is maintained for the applied load being considered in fig. 5; this can be interpreted as a «rough interface» situation. If an additional increment of load is applied (fig. 6), rotational sliding failure and lateral heaving occur. At this stage, according to fig. 4, the plate load-settlement response is still quasi-linear although the material is in an yielding state.

The general patterns of deformation in presence of the woven fabric (fig. 7) are different from those obtained without geotextile, with lesser lateral movement and settlement of the soils, although a larger load was applied. The significant reduction of the horizontal components of the displacement vectors in figs. 7 the and 8 indicates that the woven geotextile provides strong lateral confinement to the sand layer and prevents the development of the shear failure observed without inclusion. This modification of the deformation mechanism and the resulting improvement of the upper soil layer behavior are in addition to the menbrane support action provided by the geosynthetic.

4.3. *Tensile deformation of the geotextile*

Base on the observed displacements of the markers glued on the geotextile fabric, the tensile deformation of the reinforcing inclusion can be monitored. The variation of the geotextile strain with distance from the axis of the load is represented in fig. 9 for two values of the applied pressure. Very small tensile strains are developed (less than 1%) although significant reinforcement takes place at these applied loads. Maximum tensile strains occur below the edge of the loading plate and there is practically no strain developed in the central area located below the plate. This observation is consistent with the uniform deflections of the interface for this zone (fig. 7) and can be explained by the strong confinement of the sand material close to the loading plate. It is noted that the contact surface of the loading plate used in these experiments was rough.

A study was performed to investigate the accuracy of the geotextile strain determination. Uniform tensile loads were applied to fabric strips and the local strains derived from x-ray imaging were compared to the known strain. For strains ranging between 0% and 1% and a distance between markers of 40 mm, the mean value of the difference between the two quantities was close to zero an its standard deviation was of the order of 0.1 percent. This suggests that the local strains values lesser than 0.1% obser-

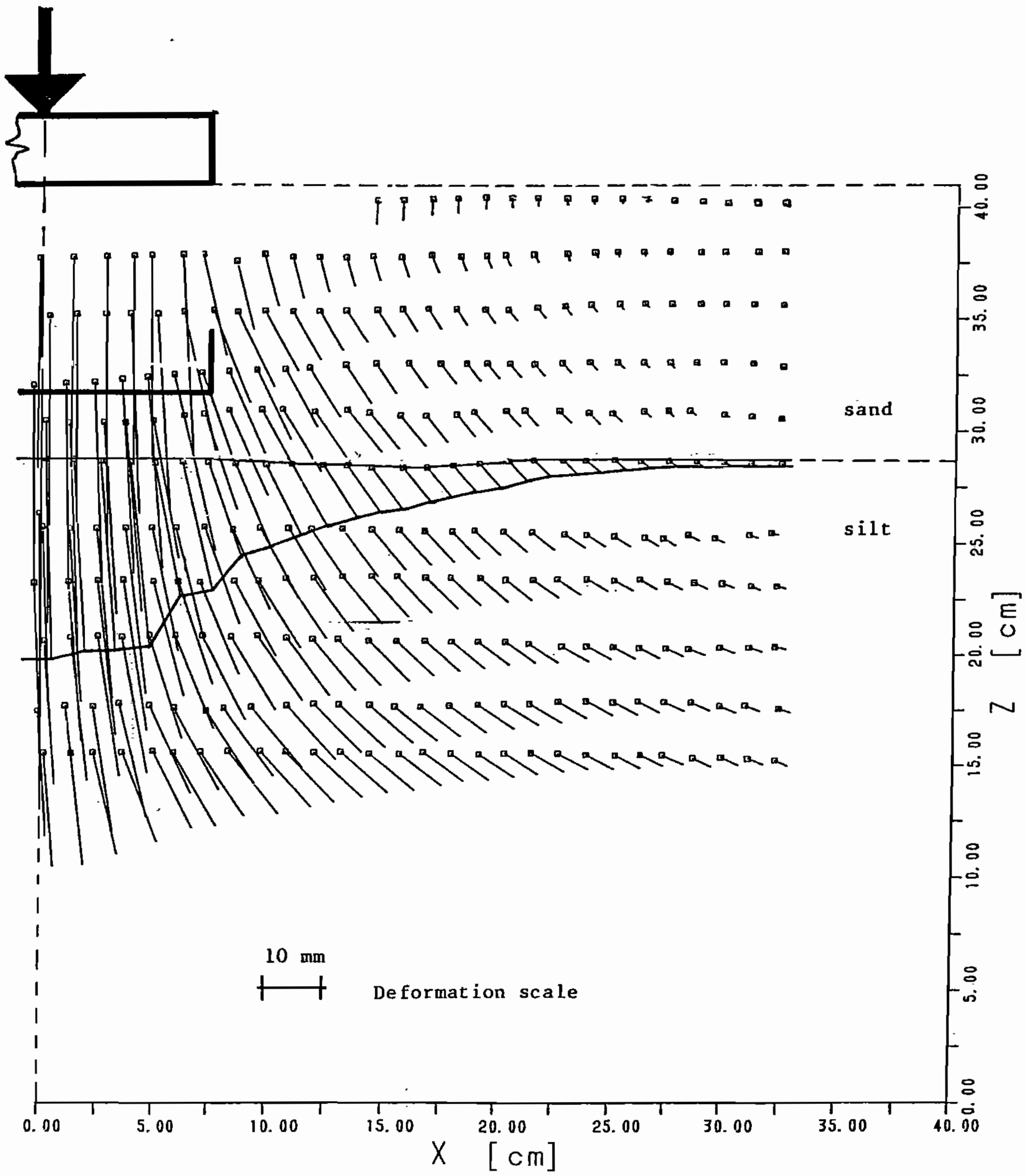

Fig. 5. - Unreinforced system - Patterns of cumulated displacement vectors for 93 kPa average applied pressure.
Sistema non rinforzato - Vettori degli spostamenti cumulati per pressione media di 93 kPa.

ved in fig. 9 are not significant. For greater deformations, the x-ray imaging technique provides reliable estimates of the strains in the reinforcement.

5. Summary and conclusions

The internal field of deformation of a two-layer soil system reinforced at the interface by geotextiles was observed by x-ray radiography. Small lead shots, 2 mm in diameter, were used as displacement markers for both the soils and the geotextile. Static loads were applied to a rough rigid plate at the surface of the model and a x-ray radiography was taken after each load increment. This technique provided detailed information on the patterns of soil deformation and on the local elogations of the fabric.

The general patterns of deformation in presence of a woven fabric are different from those obtained without geotextile: they exhibit lesser settlement and lateral spreading of the soils. The woven geotextile provides a lateral confinement to the upper sand layer and prevents development of the shear failure observed without reinforcing inclusion. This modification of the deformation mechanism is in addition to the membrane support action. Although significant reinforcing effect was achieved, the x-ray images indicate very small tensile strains in the geotextile for the applied loads being considered.

There is significant experimental evidence that x-ray imaging provides the means to determine the deformation field within laboratory scale models of reinforced systems with accuracy while minimizing both disturbance and boundary effects.

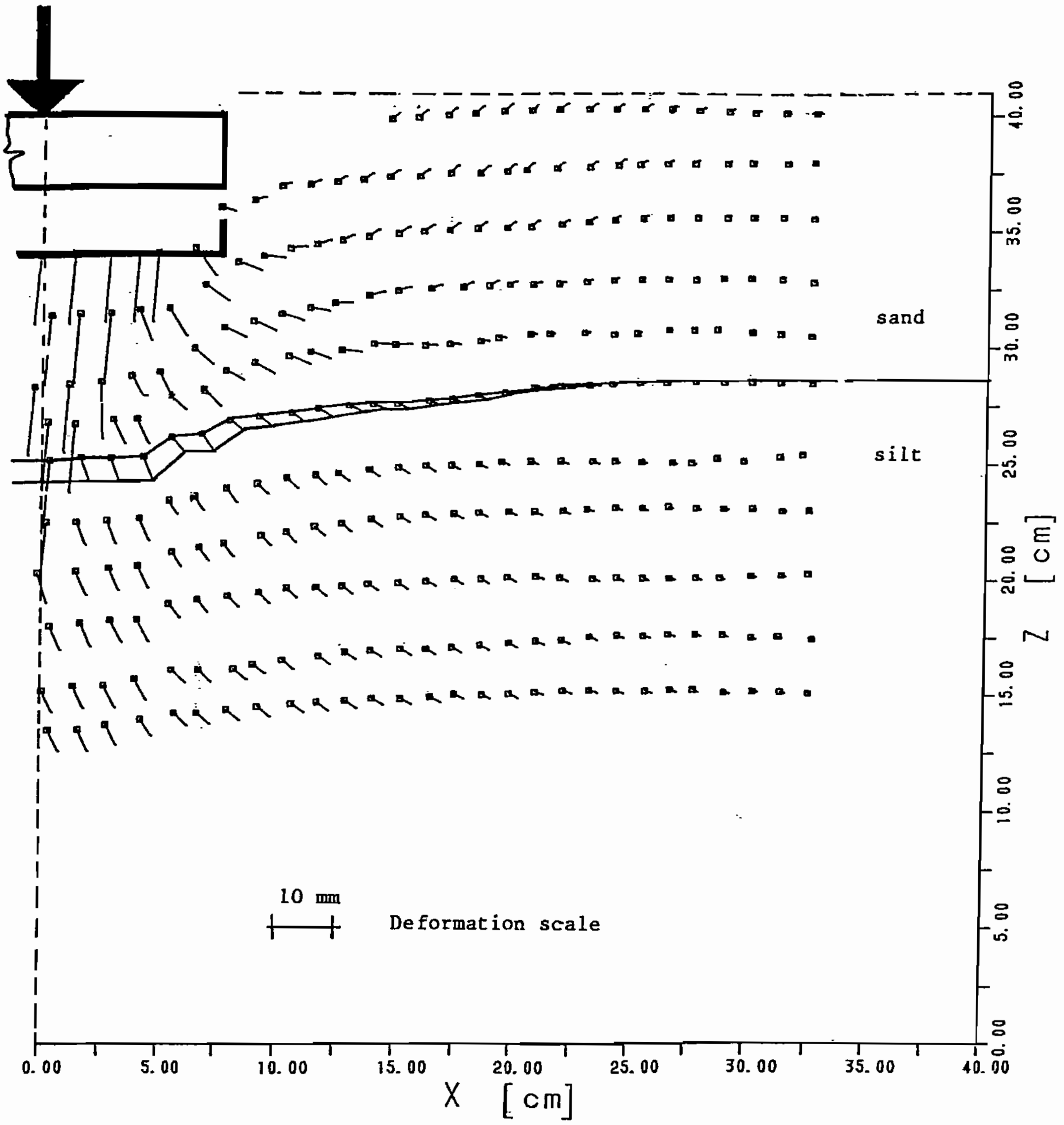

Fig. 6. - Unreinforced system - Patterns of incremental displacement vectors, applied pressure increased from 93 kPa to 124 kPa.
Sistema non rinforzato - Vettori degli incrementi di spostamento per un incremento di pressione da 93 a 124 kPa.

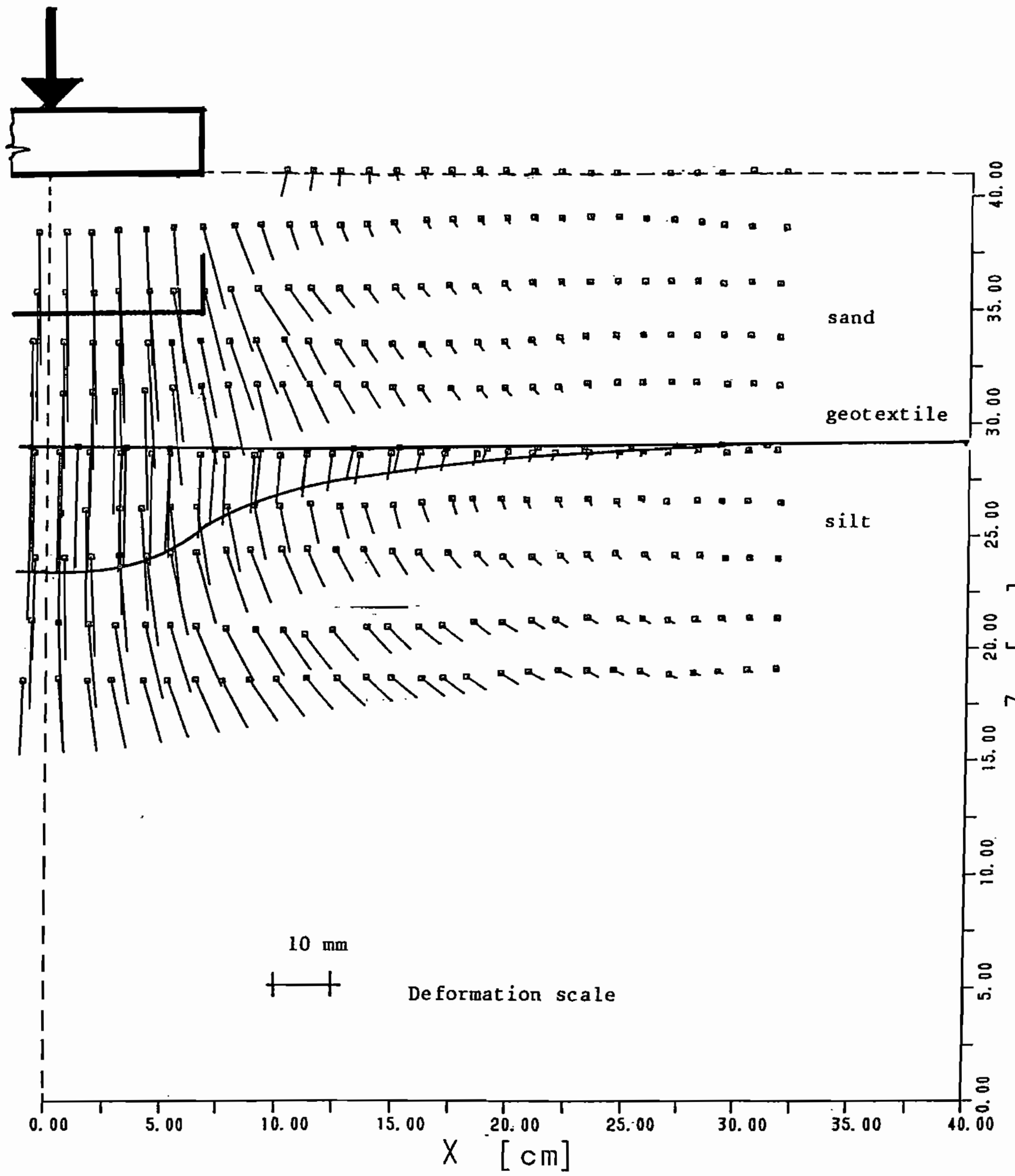

Fig. 7. - Reinforced system - Patterns of cumulated displacement vectors for 125 kPa average applied pressure.
Sistema rinforzato - Vettori degli spostamenti cumulati per una pressione media di 125 kPa.

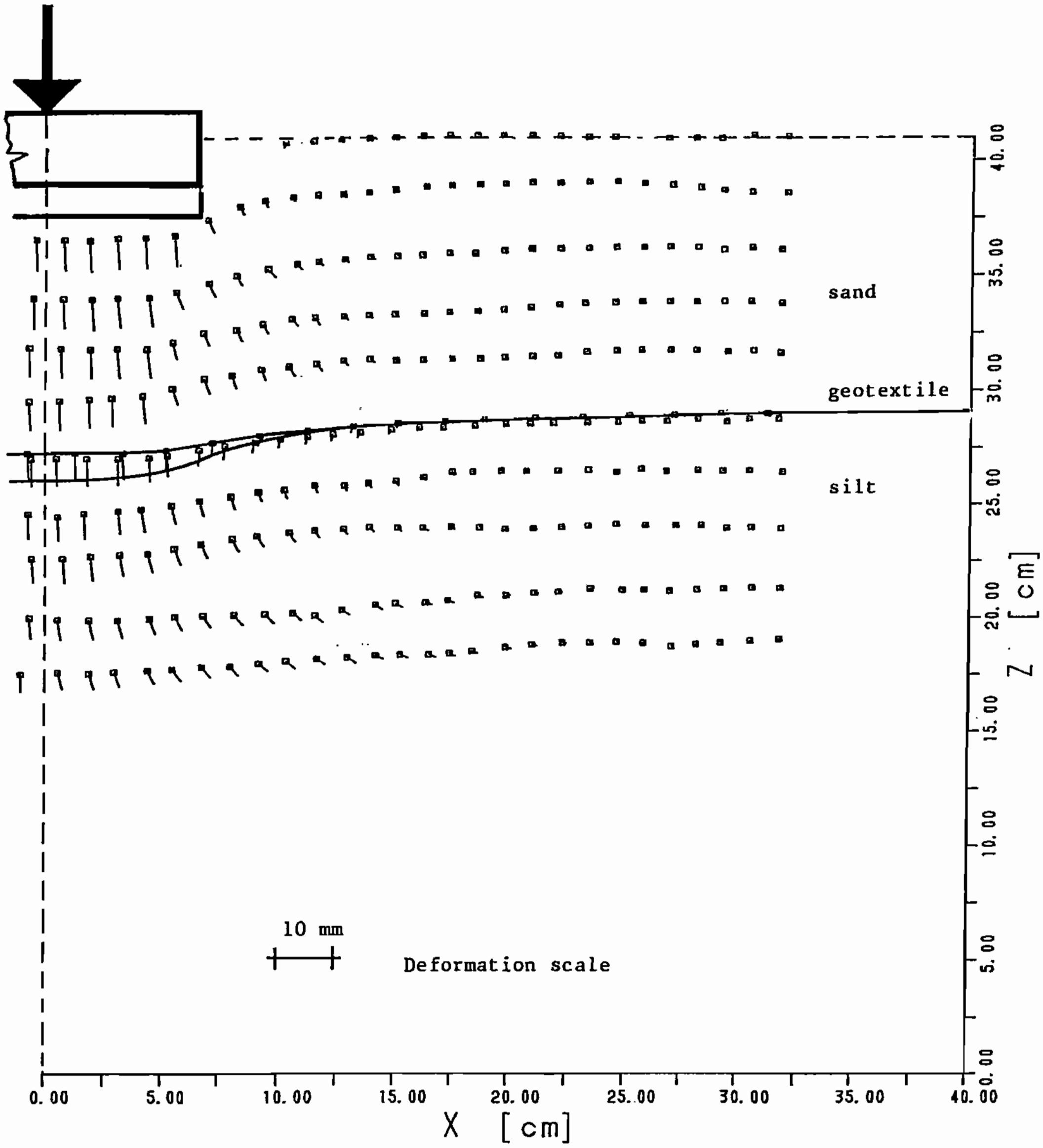

Fig. 8. - Reinforced system - Patterns of incremental displacement vectors, applied pressure increased from 96 kPa to 125 kPa.
Sistema rinforzato - Vettori degli incrementi di spostamento per un incremento di pressione da 96 a 125 kPa.

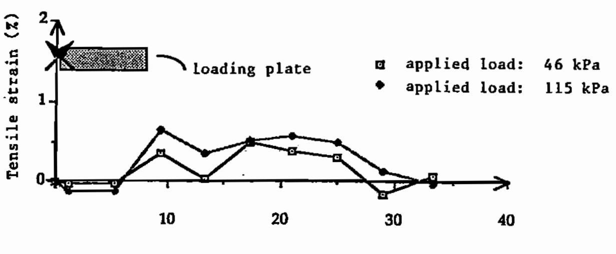

Fig. 9. - Distribution of tensile strains in the geotextile.
Distribuzione delle deformazioni di trazione nel geotessile.

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RIASSUNTO

Impiego della tecnica radiografica in problemi di interazione terreno-rinforzo

Sebbene l'interazione terreno-rinforzo dipenda essenzialmente dalla rigidezza relativa del terreno e del materiale sintetico e dalla capacità di ancoraggio di quest'ultimo, esistono pochi dati sperimentali per stabilire il contributo relativo di questi due fattori. Data la complessità del meccanismo di interazione è necessario analizzarlo su modelli in scala in laboratorio.

Fra le tecniche non distruttive proposte per osservare e quantificare il cammino della deformazione locale nei terreni con o senza rinforzo, la tecnica radiografica permette di visualizzare lo stato interno dei modelli e di valutarne la deformazione sotto carichi superficiali.

L'impiego dei geotessili in geotecnica è basato sull'idea di sfruttare la resistenza a trazione dei sintetici migliorando le proprietà del terreno, capace di resistere solo a compressione e a taglio. Il miglioramento del comportamento meccanico del terreno è dato da:

- rinforzo tridimensionale che attraverso l'inclusione di fibre nel volume di terreno, tende a creare un materiale omogeneo con valori delle caratteristiche di resistenza più alti in ogni direzione in rapporto a quelli dei terreni naturali;
- rinforzo «orientato» che tramite l'inclusione di strati di geotessili o di griglie polimeriche migliora la risposta del terreno in direzioni preferenziali secondo l'orientamento relativo dei carichi applicati e degli strati di sintetico.

In questo caso l'interazione terreno-rinforzo è dovuta principalmente a:

- mobilizzazione dell'attrito all'interfaccia con sviluppo di tensione di trazione lungo il geotessile e contenimento laterale del terreno con conseguente aumento della rigidezza e della capacità portante degli strati di terreni rinforzati;
- comportamento a membrana del geotessile, a causa del suo abbassamento, che risulta in una pressione di contatto all'interfaccia con conseguente incremento della capacità portante del terreno di fondazione (fig. 1).

L'efficacia di questi meccanismi, che agiscono separatamente e simultaneamente, dipende dall'attrito disponibile all'interfaccia terreno-rinforzo, dalla rigidezza relativa del terreno e del geotessile e dall'entità dell'abbassamento all'interfaccia.

L'applicazione della radiografia all'analisi quantitativa in geotecnica, cominciata all'Università di Cambridge, ha subito un notevole sviluppo nel campo della ricerca grazie al progresso nelle apparecchiature e al miglioramento delle tecniche di trattamento computerizzato delle immagini e dei dati.

Una ricerca sperimentale è stata condotta presso l'Ecole Polytechnique Fédérale di Losanna per studiare il meccanismo di rinforzo in sistemi formati da due strati sotto l'azione di carichi superficiali. Il geotessile tessuto era inserito fra uno strato superiore di sabbia monogranulare ed uno inferiore di limo: i due terreni erano secchi e non compattati. La geometria del sistema, i parametri dei terreni e del geotessile e le caratteristiche del dispositivo di prova sono riportate in tab. 1 e 2 e in fig. 2 e 3. Un contenitore con pareti rigide e lisce serviva per simulare uno stato di deformazione piana e carichi statici venivano applicati per piccoli incrementi attraverso una piastra rigida alla superficie del modello. Come rivelatori di spostamento sono state usate piccole biglie di piombo (diametro 2 mm.) sia per i terreni che per il geotessile. Un esperimento senza rinforzo è stato utilizzato come riferimento. Una radiografia del modello veniva presa dopo ogni incremento di carico e confrontata a quella dello stato iniziale di riferimento.

In fig. 4 è riportata la curva carico-cedimenti del corpo di carico sia per il modello con geotessile che per quello senza rinforzo: vi è un miglioramento significativo della risposta del sistema in presenza dell'armatura.

Il percorso delle deformazioni interne per il sistema senza armatura (fig. 5 e 6 - spostamenti cumulativi e incrementali) è tipico della risposta dei terreni granulari sciolti sotto l'azione di deboli sovraccarichi superficiali: abbassamento generale dei due strati con conseguente espansione laterale al di fuori della area caricata ed aumento del grado di compattazione del terreno limoso di fondazione (le scale scelte per rappresentare le distanze e gli spostamenti sono diverse). Se si applica un ulteriore incremento di carico (fig. 6), si ha una rottura per scivolamento rotazionale ed un innalzamento laterale sebbene la curva carico-cedimento (fig. 4) sia ancora quasi lineare anche se il materiale è in condizioni di snervamento.

La presenza del geotessile (fig. 7 e 8-spostamenti cumulativi e incrementali) risulta in un minor abbassamento anche per carichi applicati più elevati: questa riduzione della componente orizzontale dei vettori di spostamento indica che il geotessile causa un contenimento laterale dello strato di sabbia e previene lo svilupparsi della rottura per taglio osservata nel modello senza rinforzo. Questa variazione del meccanismo di deformazione e il risultante miglioramento del comportamento dello strato superiore di sabbia vanno ad aggiungersi al miglioramento dovuto al comportamento a membrana del geosintetico.

L'allungamento del geotessile si ricava a partire dagli spostamenti osservati delle biglie di piombo incollate lungo il materiale sintetico. Gli allungamenti calcolati (fig. 9) sono piccoli anche se l'azione di rinforzo del geotessile è significativa anche per valori bassi del carico applicato. La deformazione massima si ha in corrispondenza del bordo della zona caricata mentre non si hanno allungamenti nell'area centrale sotto la piastra, in accordo con il fatto che gli abbassamenti sono uniformi in questa zona (fig. 7): ciò può essere spiegato considerando il forte contenimento laterale della sabbia in prossimità del dispositivo di carico.

Conoscendo poi il modulo di resistenza del sintetico è possibile ricavare i corrispondenti valori di tensione lungo il geotessile.

Uno studio è stato condotto per valutare la precisione della determinazione dell'allungamento del geotessile: i valori di allungamento minore dello 0.1% (fig. 9) non sono significativi. Per deformazioni maggiori la tecnica radiografica fornisce delle stime affidabili della deformazione del geotessile.