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斜面崩壊による労働災害防止に関する研究

平成19年度　総括研究年度終了報告書

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主任研究者　三田地　利之　北海道大学　大学院　教授

研究要旨：斜面崩壊による労働災害を防止するために，斜面崩壊の防止，および発生の予知に関する研究を行った．当該年度は，地盤強度の評価法として，室内試験による地盤の引張り強度評価法の提案および新規開発した簡易静的コーン貫入試験機の現場適用可能性の検討を行った．さらに降雨による地盤の崩壊現象のメカニズムについて検討を加えるとともに，本研究で開発した高精度傾斜計による斜面変位の検知・警報システムの構築に関する提案を行った．

A. 研究目的

斜面崩壊による事故防止を目的に，崩壊防止およびその予知についての研究を行う．

B. 研究方法

的確な斜面の監視に基づき，計測データから崩壊の危険性を判定し，崩壊直前には確実に警報を発して避難することができるような簡易かつ安価でしかも信頼性の高いシステムを開発し，現場実験によって検証するところまでを研究目標にすえて，以下の４項目

１）地盤強度の評価法の検討

２）斜面変位等計測機器の試作

３）斜面の変位・崩壊の予測および危険性判定手法の検討

４）検知・警報システムの検討

について実施してきたこれまでの成果を総合的に検討し，総括を行った．

C. 研究結果

まず，斜面安定の基礎をなす地盤強度の評価法について検討し，室内試験による地盤の引張り強度の評価法および地すべり対策工設計用強度パラメータの決定法についての提案を示した上で，現場で簡便に強度評価が可能なように工夫開発した簡易静的コーン貫入試験機の原位置試験結果を示し，十分に現場に適用可能であることを示した．

つぎに，斜面崩壊の動態観測・崩壊予知に資するべく本研究で開発した高精度傾斜計を用いて実施した室内模型実験および現場実物大実験を通して，突発的に発生する小規模斜面崩壊についても崩壊の前兆現象を精度よく捉えられることを示した．さらに，降雨による地盤中の間隙水圧の挙動に関する遠心場での模型実験結果から，複数の層から成る地盤ほど崩壊が生じやすく，かつ崩壊は斜面表層に限定的に生じかつ突発的であることなどを確認した．

以上の成果を受けて，本研究で試作した斜面崩壊の検知・警報システムについて検討を加え，検知システムとして本研究で開発した傾斜計を用いる場合の警報発信レベルを提案した．

D. 健康危機情報

なし

E. 研究発表

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サクションの測定を伴う引張り試験装置の開発：第 43 回地盤工学研究発表会，広島.

F. 知的財産権の出願・登録状況

１．特許取得

なし

２．実用新案登録

なし

３．その他

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斜面崩壊による労働災害防止に関する研究

分担研究者　田中　洋行　北海道大学　大学院　准教授

研究要旨：斜面崩壊による労働災害を防止するために，斜面崩壊の防止，および発生の予知に関する研究を行った．当該年度は，透水係数の異なる２層からなる斜面地盤について降雨による地下水位の上昇と斜面の安定性に関する遠心力載荷模型実験を実施し，降雨による斜面の崩壊メカニズムに関する研究を行った．

A　研究目的

斜面崩壊の事故を防止するために，降雨による崩壊のメカニズム，およびその予知についての研究を行う．

B　研究方法

降雨による斜面崩壊のメカニズムを明らかにするために，透水性の異なる２層からなる模型地盤を作成し，遠心力載荷実験によって不飽和土における降雨による地中の間隙水圧の挙動と斜面の崩壊メカニズムについて調べた．

遠心力を平面および斜面地盤に負荷し，降雨を与えることにより，地盤内の地下水位上昇を捉えた．実験は地盤の透水係数と降雨強度および遠心力を変化させ，地下水位の上昇速度との関連の把握を目的とした．そのために，比較的透水係数が大きな２層から成る地盤を対象として，降雨による斜面崩壊を遠心力載荷模型実験によって再現した．

C　研究結果

一連の実験結果から，

１）均一な地盤より透水係数が異なる複数の層からなる地盤の方が，斜面崩壊を生じやすいこと，

２）斜面崩壊は限られた表層で起こること，

がわかった．

特に２）については，さらに破壊状況を詳細に記述すると，２～３回に分かれて斜面が崩壊していることが，実験時の観察から確認されている．したがって，このような場合には，のり肩の変位から破壊を予知することは非常に難しいことがわかる．今回行った実験では，目視では何の前兆も観察されないうちに，突然斜面表層が崩壊した．したがって，このようなケースの場合の崩壊の予知は精度の高い計測機器を用いなければ非常に難しい．計測機器による観測体制がとられていない状況下で斜面崩壊による人身事故を回避するためには，天気予報などの情報から降雨強度があるレベルを超えると作業を中止するなどの方法をとるのが最良と考えられる．

D　健康危機情報

なし

E　研究発表

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F　知的財産権の出願・登録状況

１．特許取得

なし

２．実用新案登録

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（総括）研究年度終了報告書

斜面崩壊による労働災害防止に関する研究

分担研究者　豊澤康男 独立行政法人産業安全研究所 統括研究員

研究要旨：斜面崩壊による労働災害を防止するために，斜面崩壊の防止，および発生の予測・検知に関する研究を行った．当該年度は，簡易に計測できる高精度傾斜計について中規模実験および実物大実験を行った．

A　研究目的

斜面崩壊による労働災害を防止するために，小規模で局所的な崩壊を対象とし，その崩壊の発生を検知するため，安価で効果的な計測器（高精度傾斜計）の開発・試作を行い，その有効性について検討を行う．

B　研究方法

斜面崩壊発生前の地盤の変形を検知するための計測方法として開発した「高精度傾斜計」は，斜面内に一個計測機器を設置すれば，それだけでも測定を開始できる．本研究では斜面崩壊の検出状況を確認するために，高さ1～2mの砂質土斜面と高さ5mの砂質土・粘性土斜面を作成して斜面崩壊実験を行った．

C　研究結果

実験の結果，労働災害が発生しやすい突発的で急激な小規模崩壊についても精度良い計測が可能で，崩壊直前の前兆現象を捉えることが出来ることを確認した．具体的な結論は，以下のとおりである．

1) 試料として川砂を用いて行った室内模型実験では，崩壊前に0.1度以下の微小な傾斜を捉えることが出来た．
2) 崩壊の前兆現象を表す加速度的な角度の増加を捉えることが出来るかは，設置位置に大きく依存する．今回の一連の実験では，法肩に設置した傾斜計が最も感度が良く崩壊の前兆現象を捉えた．
3) 微小な傾斜を計測するため，斜面にはある程度深くロッドなどを差し込むなど，斜面の表層変形を感度良く捉える工夫が必要である．
4) 現場における実物大実験から，砂質系地盤では室内模型実験と同様に法肩に設置した傾斜計では崩壊前に加速度的な角度の増加傾向を示し，崩壊の前兆現象を捉えることが出来た．
5) 粘性土地盤では，砂質系地盤とは異なり，崩壊する土塊上に設置された傾斜計において崩壊前に加速度的な角度の増加傾向を示し，崩壊の前兆現象を捉えることが出来た．地盤種類の違いなどによって設置位置を検討する必要がある．

D　健康危機情報

なし

E　研究発表

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サクションの測定を伴う引張り試験装置の開発：第 43 回地盤工学研究発表会，広島.

F　知的財産権の出願・登録状況

1　特許取得

なし

2　実用新案登録

なし

3　その他

なし

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斜面崩壊による労働災害防止に関する研究

分担研究者　伊藤和也 独立行政法人労働安全衛生総合研究所 研究員

研究要旨：斜面崩壊による労働災害を防止するために，斜面崩壊の防止，および発生の予測・検知に関する研究を行った．当該年度は，過去 2 年間の成果および既往の研究での計測結果をもとにして斜面崩壊の検知・警報システムの試作を行い，警報発信レベルについての検討を行うとともに，斜面の崩壊可能性を判断するための原位置強度試験機の開発・試作を行った．

A　研究目的

斜面崩壊での労働災害を防止するために，崩壊の予測・検知システムを開発することを目的として，斜面変形・崩壊の予測および計測器による計測の可能性について検討してきた成果を受け，本研究では，斜面崩壊の検知・警報システムの開発を行った．また，斜面の崩壊可能性を判断する手段として，現場にて簡易に地盤強度を測定することが出来る簡易静的コーン貫入試験機の開発を行った．

B　研究方法

労働災害を伴うような斜面崩壊は地すべり等の自然現象とは大きく異なり，時間的余裕が無く一瞬のうちに土塊の滑動が起こることや，崩壊の前兆現象が顕著に表れる場合が少ないという特徴がある．本研究では斜面崩壊の計測機器として，類似した崩壊現象を示す岩盤斜面に用いられている計測機器の中で，コストや施工性を考慮して中小規模斜面工事現場にて使用することが可能な機器について検知・警報システムを構築することとした．

C　研究結果

労働災害を伴うような斜面崩壊現象は，通常の地すべり挙動よりも微小変形にて突然崩壊に至る傾向がある．しかし，崩壊に至るまでの経時変化を見ると，崩壊領域近くでは，徐々に変形量が増大している傾向は見られる．

また，傾斜計についても掘削後に徐々に傾斜角度が増加しており，概ね 0.2 度程度の変動が見られると崩壊に至っている．これらの傾斜計の設置箇所について見てみると，崩壊直前の挙動は，傾斜角度が加速度的に増加する箇所と増加しない箇所があった．また，実験ケースによっても違いが見られた．これは，設置箇所の影響が考えられ，活動土塊内部に設置された場合には，所定の検知が行えないことを示しているものと思われる．山砂にて作成された斜面は，実際に工事を実施する現場と比べると粘着力が少ないために微小変形にて崩壊に至るものと想像される．

成田砂や関東ロームを使用して高さ 5m の模型斜面を作成し，切土掘削を再現した実物大実験によれば，崩壊前に傾斜計が加

速度的な増加傾向を示し, 0.1～0.2 度程度で崩壊に至っている傾向が見られる.

以上の結果から, 傾斜計の崩壊発信レベルとして,

1. 傾斜角度が累積で 0.1～0.2 度となった場合, および,
2. 傾斜角度の変化が加速度的に増加する傾向が見られる場合

に警報を発信することを提案した. 今後, 多くの地盤について実地設置し, データの蓄積を行いながらこれらの閾値を精度良くすることが重要であろう.

本研究では, 上記に加えて斜面の崩壊可能性を判断する手段として, 現場にて簡易に地盤強度を測定することが出来る簡易静的コーン貫入試験機を開発した. これは従来の静的コーン貫入試験と簡易動的コーン貫入試験やポータブルコーン貫入試験の中間に位置し, 精度が高い計測結果と簡易性・利便性を確保することをねらったものである. 現場実験の結果から, 手軽に持ち運びが可能で, かつ十分に現場に適用可能であることが検証された.

D　健康危機情報

なし

E　研究発表

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高精度傾斜計による土砂崩壊事前予知の可能性について―現場模型実験等の結果から―, 第 42 回地盤工学研究発表会, 名古屋.

F　知的財産権の出願・登録状況

1　特許取得

伊藤和也 : 折りたたみ式静的コーン貫入試験装置, 特願２００７－２０１７２１

2　実用新案登録

なし

3　その他

部分意匠登録出願

伊藤和也 : クランプ折りたたみ式静的コーン貫入試験装置, 意願２００７－０１９６１９

Ⅲ　研究成果の刊行に関する一覧表

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Ⅳ　研究成果の刊行物・別刷り

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MEASUREMENT OF SOIL TENSILE STRENGTH AND FACTORS AFFECTING ITS MEASUREMENTS

Surendra Bahadur Tamrakar[i], Toshiyuki Mitachi[ii] and Yasuo Toyosawa[iii]

ABSTRACT

This paper describes the tensile strength measured for three kinds of statically compacted unsaturated soils; mixtures of clay ~ silt ~ sand, Narita-sand and Kanto loam. Specimens were directly prepared either under controlled compaction stress or under controlled dry density by statically compacting them within the tensile mold of the apparatus. Image analysis was done to show the normality of tensile force to the tensile failure plane. Tensile strengths (q_t) were compared with the unconfined compressive strengths (q_u) for silt ~ sand mixture, clay ~ sand mixture, clay ~ silt mixture and Narita sand, respectively. Increment in tensile strength (also q_u/q_t ratio) with the increase in the percentage and decrease in the size of finer soils could be seen. Effects of number of compaction layers and tensile pulling rates on the q_t were also examined. Increase in the tensile strength with the increase in the number of compaction layers was observed; and it was suggested to prepare the unsaturated compacted specimen by 3 to 4 layers compaction. Increase in tensile strength of 0.3 kPa and 0.003 kPa per one cycle of logarithm of tensile pulling rate was observed for clay ~ sand-4 (1:3) and clay ~ sand-5 (3:1) for the pulling rate of 0.01 to 1.0 mm/min.

Key words: compacted soil, rate effect, tensile strength, test equipment (**IGC:** D6/D9)

INTRODUCTION

Most of the vertical slopes get failed with the development of tensile crack on the top of the slope. Also, many earth dams, embankments, pavements, etc. where soil layers are compacted, are failed due to the development of tensile cracks. Prediction of probable position and depth of tensile crack is necessary to protect the property and loss of lives of workers at the construction site. In order to explain the position and depth of tensile crack, an accurate measurement of tensile strength of soil is necessary. Very few researches (e.g., Suzuki et al., 1998; Yao et al., 2002; Ono et al., 2003) have been made to measure the tensile strength of soils having lower tensile values. Recently, Nahlawi et al. (2004) and Tamrakar et al. (2005a) have introduced a new tensile strength measuring apparatus which measures the tensile strength directly. One developed by Nahlawi et al. (2004) could be mainly used for compacted clayey and stiff soils only whereas the one developed by Tamrakar et al. (2005a) seems to be easy to use and simple to handle and could be used for both compacted unsaturated and highly saturated soils.

Tamrakar et al. (2005a, b) measured the maximum tensile strength of Kanto loam around 50 ~ 60% of water content and showed the ratio of q_u/q_t around 12.5 which varied with the water content. They also showed the effect of the amount of finer particles and their size on tensile strength. Possible measurement of tensile strength for saturated NSF clay was also shown. Jung et al. (2001) had conducted tensile tests for dry and wet rock specimens, and mentioned about the strain rate effect. Nahlawi et al. (2004) had mentioned about the change in tensile displacement rate while tensile pulling was done at the constant speed depending upon the stiffness of the test specimen. But the research on the effect of tensile pulling rate on soil has not been carried out yet.

In this paper, tensile apparatus (type-A tensile mold) developed by Tamrakar et al. (2005a) was used and the normality of tensile pulling force in respect with tensile failure surface was shown by carrying out image analysis. Also, the effect of the number of compaction layers and tensile pulling rate on the tensile strength of compacted specimens of clay and clay ~ sand mixtures is explained. In addition, unconfined compression tests were also performed and their values were compared with tensile strength.

TEST EQUIPMENT

Tensile test apparatus shown in Photo 1 consists of horizontal platform upon which apparatus box having two halves; fixed box and movable box, is placed. Inside this box, two tensile molds are placed. The inner shape of

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a mold is like "C" structure and it holds the specimen. Two molds are screwed to the apparatus boxes separately. One box of the apparatus is fixed to the horizontal platform while the other box can move freely on the horizontal platform. To reduce the friction, linear sliding rollers are placed between the movable box and platform. Movable box is pulled away in horizontal direction until the soil specimen fails in tension with tensile crack appearing at the middle of the specimen where two halves of the mold is attached. A load cell placed between the movable box and motor axis measures the tensile load. This tensile load divided by the area of the tensile crack perpendicular to horizontal pulling direction gives the tensile stress. The minimum width at the constricted section of the mold is 3 cm and the depth is 5 cm. The apparatus box along with the mold and platform can be completely separated from the motor for preparing the specimen before the test. Compacted soil specimen is prepared within this mold by direct static compression. Once the specimen is ready within the mold for the test, then it is connected to motor shaft.

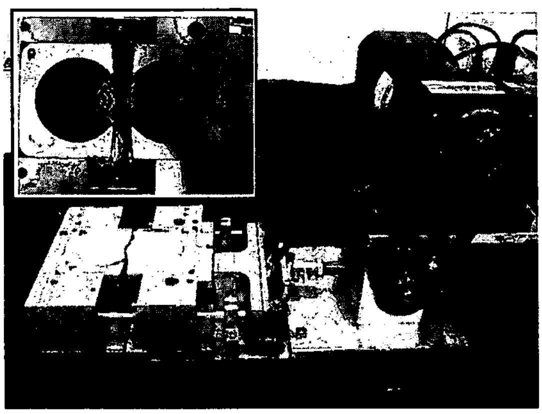

Photo 1. Tensile stress apparatus

SPECIMEN PREPARATION

Mixtures of NSF-clay ~ CFP-silt and Toyoura-sand (clay ~ silt ~ sand), Narita sand, and Kanto loam were taken as test materials. NSF-clay is commercially available clay which consists of Pyrophylite, CFP-silt (100) is crushed form of Silica sand, and Toyoura sand which was formerly standard sand in Japan is also commercially available. Narita sand and Kanto loam soils were sampled from Toke excavation site of Chiba prefecture, Japan. Grain size distribution curves and index properties for these soils are shown in Table 1 and Fig. 1. Narita sand used here is classified as SF. Now onwards, NSF-clay, CFP-silt and Toyoura sand are represented by clay, silt and sand, respectively.

Before preparing the specimens, at first, tensile molds were fixed into the apparatus box and screwing was done between the movable box and apparatus horizontal plate so that movable box would be fixed. To reduce the friction between the specimen and the inner wall of the tensile mold, thin film of grease was applied over its inner surfaces. After the completion of compaction of specimens into the tensile mold, load cell was set up towards the pulling side of mold box. Finally, the screws which were fixed to prevent the movement of movable box of

Table 1. Index properties

Materials	ρ_s	w_L	w_P	ρ_{dmax}	ρ_{dmin}
	g/cm^3	(%)	(%)	g/cm^3	g/cm^3
Kanto loam	2.65	143.5	74.6		
NSF-clay	2.78	55.1	30.6		
silt (CFP-100)	2.66			1.59	1.17
Toyoura sand	2.64			1.65	1.34
Narita sand	2.61				

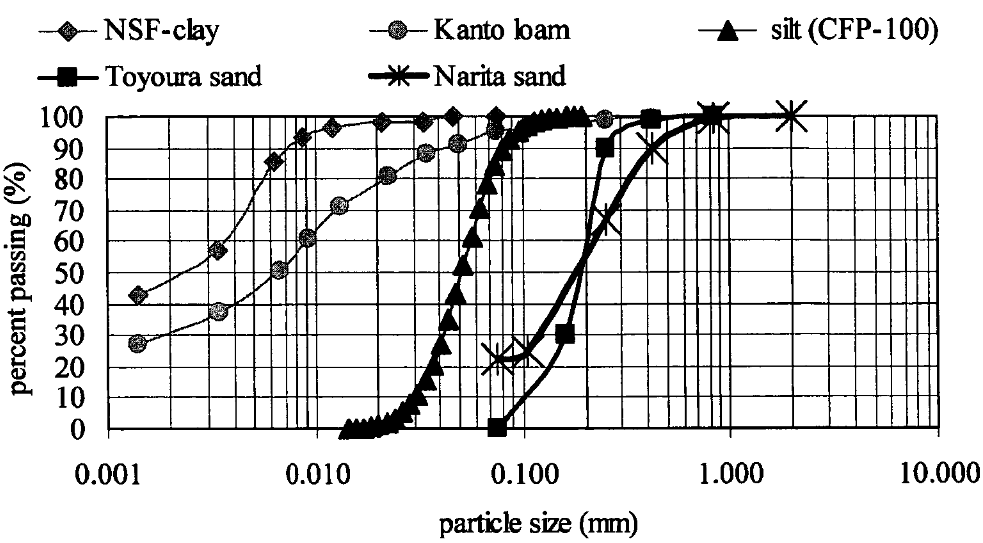

Fig. 1. Grain size distribution curves

Table 2. Reference tests and q_u/q_t ratio for mixtures

(w=10%, H=5 cm, one-layer compaction, tensile pulling rate=0.34 mm/min)

Dry density	NSF-clay	CFP-silt	Toyoura sand	q_u	q_t	q_u/q_t
(g/cm³)	%	%	%	(kPa)	(kPa)	
1.5	40	—	60	55.9	6.6	8.4
	50	—	50	74.4	7.8	9.5
	60	—	40	79.1	8.6	9.2
1.5	25	75	—	64.3	6.9	9.3
	40	60	—	100	8.4	11.9
	50	50	—	97.8	8.5	11.5
	60	40	—	132.2	10.3	12.9
	75	25	—	182.2	11.7	15.5
1.4	—	25	75	6.6	1.4	4.6
	—	40	60	12.9	2.2	6
	—	50	50	16.4	2.7	6.1
	—	60	40	18.7	3	6.2
	—	70	30	26.7	3.9	6.9
1.5	33.3	33.3	33.3	50.3	5.9	8.6

the apparatus were un-screwed.

Before making specimens, materials were thoroughly mixed with required distilled water and kept in an air tight container so that water was uniformly distributed throughout the materials. Specimens were prepared either under controlled dry density or under controlled compaction stress conditions. To determine the desired compaction stress as well as dry density (or wet density), stress-density tests were carried out separately in advance. Once the compacting stress or dry density was fixed, then in both conditions, specimens were prepared by directly and statically compressing the prerequisite amount of soil kept within the tensile mold of the apparatus. In case of one layer compaction, whole amount of soil was used at once whereas in multi-layer compaction, the perquisite amount of one layer was divided by the total number of compaction layers and under each compaction layer, such divided amount of soil was added and compressed. Statically loading system with bellofram cylinder was used for compression. Collar was generally placed over the tensile mold to prevent falling out of soil specimens from the tensile mold. Effect of density on the tensile strength was already discussed by Tamrakar et al. (2005a). So, here in this research, only one density was chosen for each group of tests. The samples of clay~silt, clay~sand and silt~sand mixtures shown in Table 2 were made by mixing the materials at different proportions under controlled dry density with one layer compaction. Here the water content (w) for all the specimens was fixed to 10%. Narita sand specimens shown in Table 3 were prepared under controlled compaction stress with one layer compaction. Water content of the test specimen was maintained at around 26% to approximate the field condition. Similarly, in Table 4, Kanto loam, clay~sand mixtures and Narita sand other than those shown in Tables 2 and 3 are shown. Number of compaction layers and pulling rates were varied according to the type of the tests as shown in Table 4. To compare the tensile strength with unconfined compression strength, specimens for the materials shown in Tables 2 and 3, unconfined compressive tests were carried out. For this, test specimens were prepared either under controlled dry density or under controlled compaction stress with one-layer static compaction by using bellofram cylinder. Other conditions such as dry density and water content were kept at the same condition as those for tensile test specimens shown in Tables 2 and 3.

Table 3. q_u/q_t for compacted Narita sand

Compressive stress	w*	q_u	w**	q_t***	ϕ_u/q_t
kPa	%	kPa	%	kPa	
50	26.8	8	26	1.4	5.7
100	26.2	11	26	1.42	7.7
193	26.3	15.4	25.8	1.87	9.4

* for q_u test
** for q_t test
*** reference tests

TESTING CONDITIONS

Tests in which specimen thickness was maintained at 5 cm with one-layer compaction and pulled under 0.34 mm /min tensile pulling rate, were considered as reference

Table 4. Test materials and test conditions

Specimens	Mixing ratio by weight	w %	Controlled: dry density (ρ_d) g/cm³	Controlled: Compressive stress kPa	ρ_d[(**)] g/cm³	Conditions
Kanto loam		85.0		200	0.58	No. of layers[1,(*)]
clay ~ sand-1	3:1	10.3	1.5			No. of layers[1,(*)]
clay ~ sand-2	1:3	8.2		200	1.48	No. of layers[2,(*)]
clay ~ sand-3	3:1	7.0		200	1.26	No. of layers[2,(*)]
Narita sand-1		28.3		50	1.19	No. of layers[2,(*)]
Narita sand-2		26.0		100	1.19	No. of layers[3,(*)]
Narita sand-3		25.3		193	1.28	No. of layers[1,(*)]
clay ~ sand-4	1:3	8.2		200	1.5	Pulling rate[(a),4]
clay ~ sand-5	3:1	6.2		200	1.28	Pulling rate[(a),4]

[1]one, two and four layer-compaction, [2]one, two, three and four layer-compaction, [3]one, three and four layer-compaction, [4]four layer-compaction [(a)]0.01, 0.14 and 1.10 mm/min, [(*)]0.34 mm/min, [(**)]targetted dry density

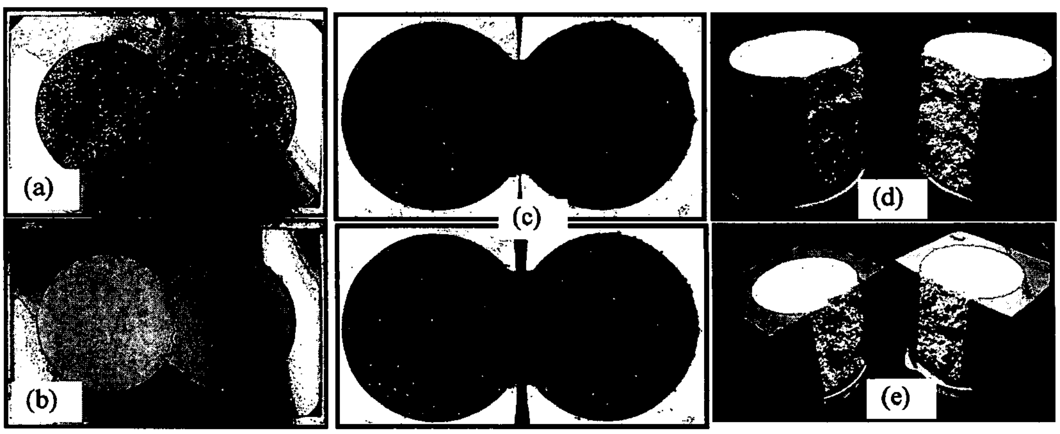

Photo 2. Tensile tests (a) for clay ~ sand-4 (after), (b) for clay ~ sand-5 (after), (c) for Narita sand-1 (before and after), (d) failure plane for clay ~ silt ~ sand (1:1:1) and (e) for failure plane clay ~ sand (1:3)

tests. Test specimens for the materials shown in Tables 2 and 3 were reference tests. To check the effect of number of compaction layers and tensile pulling rates, specimens shown in Table 4 were used. In case of the test where the effect of number of compaction layers was investigated, 5 cm thick specimens was prepared by compacting the predetermined amount of test materials with 1, 2, 3 and/or 4 layers (Table 4). Similarly, for the investigation of the effect of tensile pulling rate, 5 cm thick specimens prepared with four layer compactions were used and they were pulled under 0.01, 0.14 and 1.10 mm/min (Table 4). Unconfined compression test specimens, 5 cm in diameter and 10 cm in height, were prepared using ordinary splitting mold. Unconfined compression tests were conducted at constant displacement rate of 0.1 mm/min.

RESULTS AND DISCUSSIONS

Photos 2(a) and (b) showed the photographs after the tensile failure for clay ~ sand-4 and 5. Almost straight tensile failure crack could be seen. In Photo 2(c), photographs before and after the tensile test for Narita sand (compacted under 50 kPa) was shown. Here also, almost straight tensile crack along with target points was seen. In Photos 2(d) and (e), failure planes (tensile crack plane) after the tests for clay ~ silt ~ sand (1:1:1) and clay ~ sand (1:3) were shown. In both cases, clear and smooth failure surfaces could be seen.

As shown in Photo 2(c), 15 target points were marked on the surface of the specimen (3 rows and 5 columns) before the start of the test and photographs were taken before, during and after the test. Relative movements of target points along X and Y directions in respect with the photo before the start of the test were then compared. Here, movement along X direction represents the movement of tensile mold along tensile pulling direction. In contrary, movement along Y direction represents the movement perpendicular to tensile pulling direction. Dis-

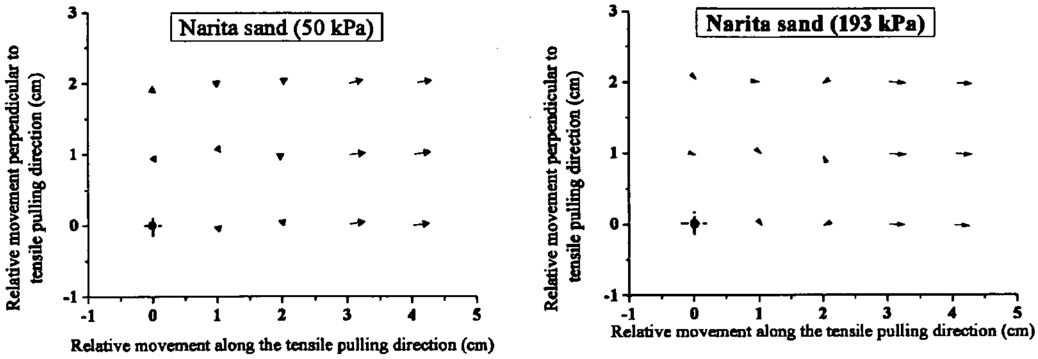

Fig. 2. Movements of points during tensile pulling for Narita sand

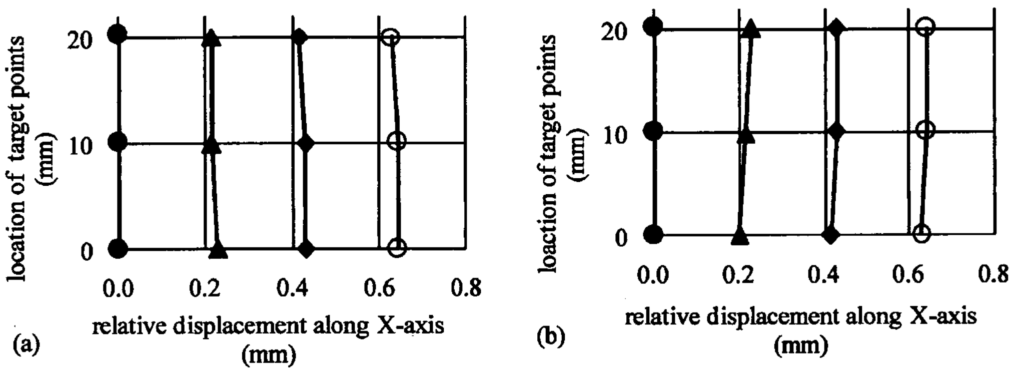

Fig. 3. Displacement of target points during pulling (a) 4th column points and (b) 5th column points

tance between each target points at the beginning is 1 cm. Here, the target point of the first column and first row is considered as reference point. Relative movements of all other target points along and perpendicular to tensile pulling direction are then made with this reference point. In Fig. 2, relative direction and amount of movement after the test for Narita sand specimens compacted under 50 and 193 kPa are shown. Almost no movement was seen for the target points of the first three columns. Target points on the 3rd column lie on the mid portion of the specimen. To locate the target points during image analysis is difficult for these mid points. But targets of 4th and 5th columns showed large movement in both specimens shown in Fig. 2. Relative displacement along X-axis observed for 4th and 5th column target points located at Y $=0$, 10 and 20 mm after the completion of tests were almost straight, showing the movement of movable tensile mold perpendicular to tensile failure plane. In addition, both the columns move similar amount of displacement.

In Fig. 3, relative displacements for target points of 4th and 5th columns are shown with the progress of the tensile pulling for the Narita sand compacted under 193 kPa. In case of Narita sand, the maximum tensile stress (tensile strength, q_t) occurred around 0.1 mm displacement. As the displacements shown in Fig. 3 started from 0.2 mm, the data observed were after the peak tensile stress. For the reference of tensile pulling positions, tensile stress vs.

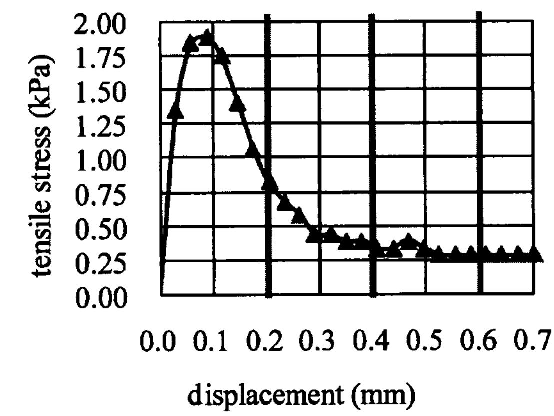

Fig. 4. Tensile stress vs. displacement curve for Narita sand (193 kPa)

displacement curve shown in Fig. 4 could be seen. (In this paper, tensile stress values are shown as positive). Unfortunately, data before the peak strength (tensile strength) could not be obtained. All the lines joining the target points for each step of movement shown in Fig. 3 are not perfectly straight lines. Little deviation in the points might have occurred during positioning the target points for image data. In overall, the directions of movement of target points of 4th and 5th columns are almost perpendicular to tensile plane. Hence, it could be said the tensile force measured with this apparatus acts perpendicularly

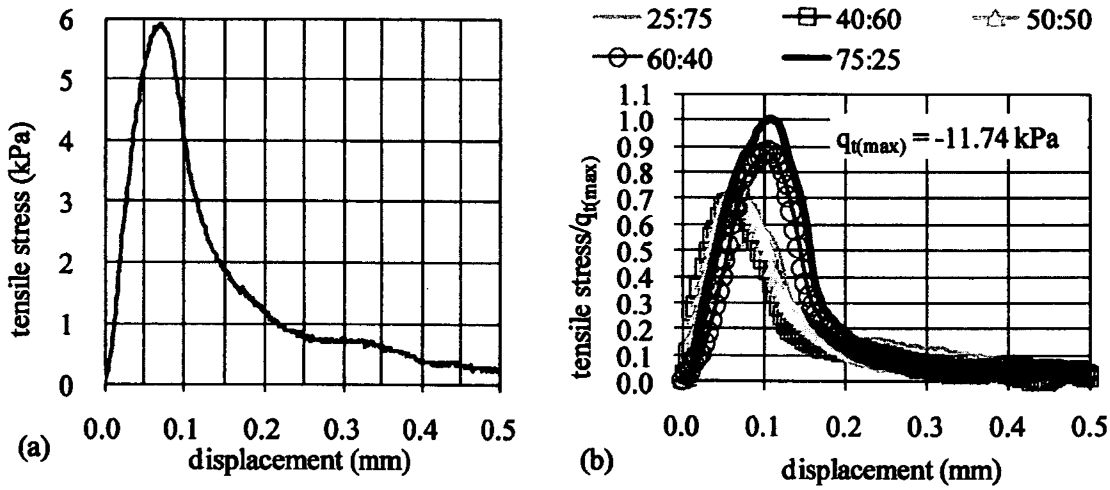

Fig. 5. Tensile stress vs. displacement curves (a) clay ~ silt ~ sand mixture and (b) clay ~ silt mixture

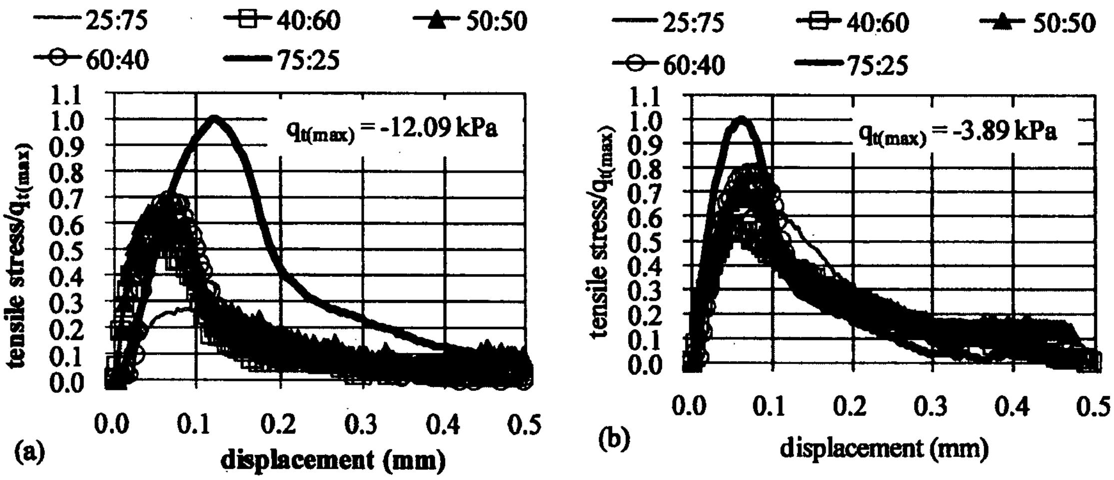

Fig. 6. Tensile stress vs. displacement curves (a) clay ~ sand mixture and (b) silt ~ sand mixture

on the tensile failure plane.

Tensile stress vs. displacement curves obtained for the mixtures of clay ~ silt ~ sand (1:1:1) was shown in Fig. 5(a) as a typical example. In Figs. 5(b), 6(a) and 6(b), normalized tensile stress (tensile stress/$q_{t(max)}$) vs. displacement curves for different mixtures of clay, silt and sand were shown. Here, $q_{t(max)}$ represents the maximum tensile strength in that group of mixture. Normalization of tensile stress with $q_{t(max)}$ in each group was done so that the effect of finer particles in each group as well as among the different groups could be compared. In addition, relative tensile strengths could be seen. In each figure clear peaks for tensile stress could be seen. In average, tensile peak values lied within the displacement range of 0.05 to 0.15 mm. By the way, peak values of unconfined compressive strength, q_u lied within the displacement range of 1 to 2 mm (not shown).

In Tables 2 and 3, q_u and q_t measured for different mixtures and Narita sand were shown. Comparing the ratio of q_u and q_t, it was found that the ratio q_u/q_t varied from 4.6 ~ 6.9, 6.5 ~ 10.9, 9.3 ~ 15.5 and 5.7 ~ 9.4 for silt ~ sand mixture, clay ~ sand mixture, clay ~ silt mixture and Narita sand, respectively. In Fig. 7, effect of finer particles on tensile strength (q_t) and strength ratio (q_u/q_t) are shown. Increment in q_t and strength ratio (q_u/q_t) with the increase in the percentage of fines and decrease in the size of finer soil particles in the soils could be seen. Similar trend of increment in tensile strength with the increase in percentage and size of finer particles had been shown by Tamrakar et al. (2005b). Increment in the tensile strength with the increase in the clay fraction was also shown by Barzegar et al. (1995).

The effect of the number of layers of compaction on tensile strength is shown in Fig. 8. Increment in tensile strength with the increase in the number of compaction layers could be seen except for some specimens like clay ~ sand-1, clay ~ sand-2 and Narita sand-2 where no increment was observed. But the overall trend of tensile

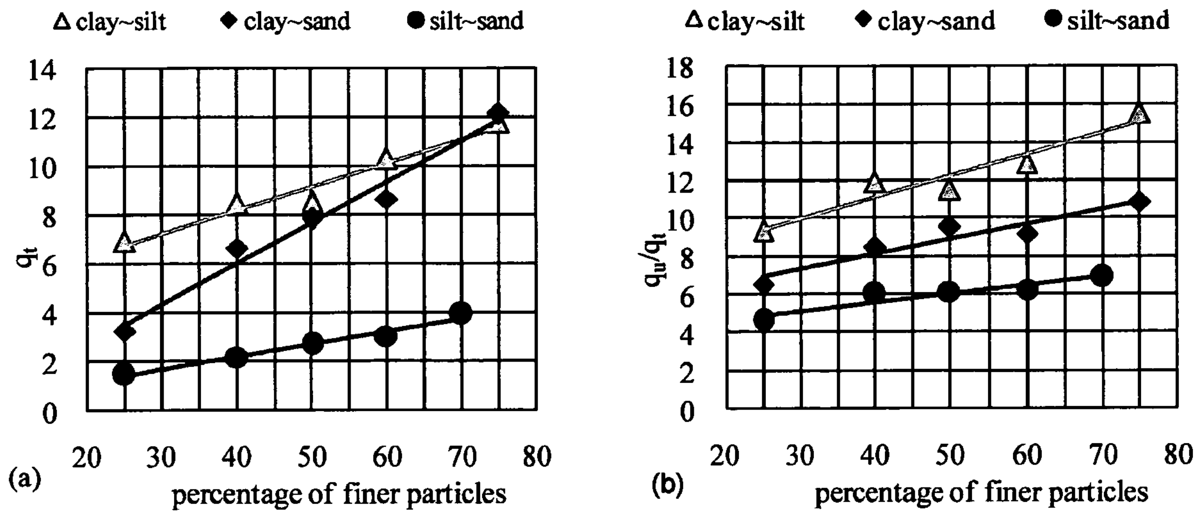

Fig. 7. Effect of percentage of finer particles (a) on tensile strength and (b) strength ratio

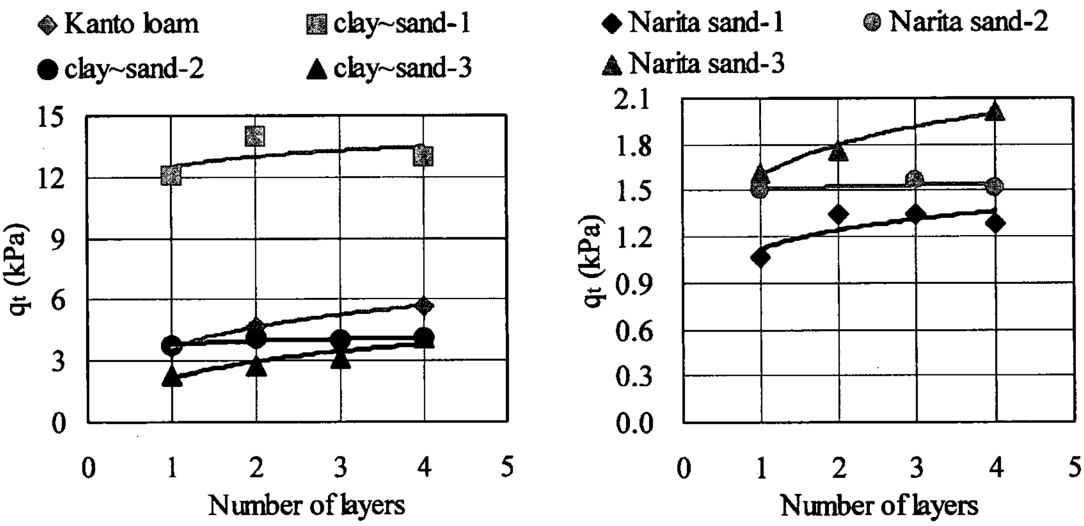

Fig. 8. Effect of number of compaction layers on tensile strength

strength increment with the number of compaction layers was in asymptotic manner. Therefore, in order to reduce the effect of number of compaction layers on tensile strength measurement, it is suggested that the unsaturated compacted specimens be prepared with three or more layers of compaction.

Effect of tensile pulling rate on tensile strength is shown in Fig. 9 for clay ~ sand-4 and clay ~ sand-5. Tensile pulling rates varied from 0.01, 0.14 and 1.10 mm/min. During the test, the whole apparatus along with the test specimen was covered by the plastic box to keep the water content of the specimen constant to prevent any change in suction value. As shown in the figure, it was observed that with the increase in the tensile pulling rate, there was an increase in the tensile strength and the slope of tensile strength versus logarithm of pulling rate is about 0.3 kPa for clay ~ sand-4 (1:3) and 0.003 kPa for clay ~ sand-5 (3:1). Also, from the graph, it could be seen that the increment is higher for the mixture having lower amount of finer particles (clay ~ sand-4 (1:3)) than that having higher amount of finer particles (clay ~ sand-5 (3:1)). Jung et al. (2001) had conducted Brazillian tests for some rocks and showed similar trend of increment in tensile strength with the increase in strain rate.

CONCLUSIONS

From the tests conducted, the following points can be concluded;

1. Clear and sharp peaks observed in tensile stress vs. displacement plots showed the possibility of measuring tensile strength with this apparatus.
2. Image analysis done for the photographs taken during the test showed that the movable tensile mold of the apparatus moved in perpendicular direction to tensile failure plane or tensile crack. Comparing the