Soil-solid interface shear strength review and its possibility on interlayer slope stability analysis

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Abstract. A landslide has been one of the many problems in geotechnical engineering, whereas, from one of the cases, a failure happened at the interface layer between the overburden and its underlying soil. As interface shear strength has become one of the growing topics in research, this paper summarizes and discusses the research development of interface shear strength and its possibility to explain the interface shear behavior at a slope. The discussion was limited to cohesive soils and experiment-based behavior of the interface shear. Some research has been selected in order to understand the development of interface shear strength through time and two examples of slope interlayer shear behavior were selected. It was known that there are three common tests of interface shear behavior used: simple shear, direct shear, and ring shear test. The development of interface shear strength started at 1960s between soil and construction materials where the four major components were defined. As the research grows, many other types of soils, interfaces, and the effect of the tests became the topic of the research. In the end, the examples given from modeling the interface shear behavior from a slope gives a new perspective of cases for interface shear strength in slope analysis.

Keywords: interface, slope stability, shear strength, soil-solid

1. Introduction

Landslides have been one of the many problems in geotechnical engineering that is still greatly analyzed until the present. One of the intriguing cases was the Semarang-Bawen landslide in 2015 that happened after it was cut, which was soon analyzed to happen due to the weathered condition of the underlying clay shale soil [1]. The landslide that happened was thought to be due to two types of failure, namely the stress release of the clay shale layer due to the construction process at the slope and the failure that actually happened at the interface layer between the overburden soil and the underlying clay shale layer [2]. From the two failure types, the interface failure landslide also happened in an earthquake-induced landslide in Japan, whereas the failure was initiated at a different strength of cemented soil layers along the discontinuous surface [3].

From the cases previously stated, it can be seen that interface shear behavior has become an important issue to understand in determining the landslide behavior of heterogeneous layers. At the beginning of the interface shear behavior theory, the interface has been limited to soil with construction materials [4]. It was known then that between soil and construction materials, different cohesion and friction angle can be determined as a mean of skin friction from the soil to the surface of the construction materials. As the knowledge of interface shear behavior grows, many tests were conducted on different soils and surfaces to understand the behavior on the different material boundary. In order to understand the development of the interface shear strength in recent years and the possibility of applying the experiment for the slope stability cases, this paper aims to summarize and discuss research on the interface shear strength in general. Although the type of soil in interface shear strength is not limited to cohesive soils, the granular soil will not be discussed as it has been thoroughly summarized in previous research [5].

2. Methodology

In order to incorporate the interface shear strength for interface analysis of slope stability, a short systematical review of the interface shear behavior would be presented. The literature given in this paper comes from different timelines, but will only be limited to a couple of sources in order to get a general view on the development of the issue. As it is well-known that interface shear strength is mostly divided into the experimental of soil-solid materials and the soil-geosynthetic materials, this paper will only focus on the soil-solid materials interface. This paper main topics will be divided into the test devices for interface shear strength, the development of soil-soil and soil-solid interface shear strength, and the examples of interface shear strength in slope stability. There are some limitations in the discussion such as the development of the test apparatus for the interface shear strength will only be discussed briefly which will emphasize on giving information of the commonly used interface shear strength apparatus, the soil considered will only be limited to the cohesive soil of clay in general, and the review will only focus on the experimental shear behavior.

3. Result and Discussion

3.1. Tests for Interface Shear Strength

One of the earliest comparisons on the interface shear strength testing method was done in 1986, where two tests, namely the simple shear and direct shear tests, were analyzed [6]. Although it was meant for the dry sand interface with mild steel, the effect of the two tests was described as having a poor significance on the coefficient of friction at the interface at yield.

Afterwards, several attempts were made in developing the effect of the tests conducted in the interface shear behaviour of both soil-on-soil and soil-solid interfaces, such as Tilt Table Device, Cam-Shear Device, UWA Small-scale Direct Shear Box, and Full-Scale Pipe-Soil Model testing at Large Scale Tests, mainly for the low effective stress condition [7]. Even though many devices were developed, the mechanism of the interface shear strength still referred to the three most commonly used tests: direct shear test, simple shear test, and ring shear test. In addition, the latter test was divided into two apparatus called the Bromhead-Type ring shear test and the Bishop-Type ring shear test [7].

From the three main types of tests described by the aforementioned research, further research was done in accommodating the effect of displacement and rate to the interface shear strength. An example of both effects in clay concluded that large displacement would increase the shear resistance due to an accumulation of the degraded material in the soil near the interface, whereas shear rate would eventually give higher peak and residual strength due to the disorder of the oriented shear zone [8].

Following the previous research, an experimental test was conducted to learn the behavior of interfacial shearing between cohesive soils and solid materials from pre-peak to post-peak strength at residual condition [9]. The study showed that shear behavior could eventually change within large displacement shearing and that the stress-tangential displacement behavior depended on the roughness and average diameter of the soil particles.

In summary, it can be concluded that there are three mainly used shear test for determining interface shear strength: simple shear test, direct shear test, and ring shear test. In addition, the displacement and rate of the test should be carefully adjusted since it will give an effect on the result.

3.2. Soil-Soil and Soil-Solid Interface Shear Strength Development

Many authors stated that the start of interface shear strength study started in 1961, where the study focused mainly to determine the values of skin friction between different types of soils (sand, clay, and granular soil mixed from both sand and clay) and construction materials (steel, concrete, and wood) [4]. The research was conducted with a stress-controlled and strain-controlled shear box for the variation of soils and construction materials. From this study, it can be concluded that there were four major points in determining the skin friction value and behavior: moisture content, surface roughness, composition of soils, and intensity of the normal load. The research also stated that adhesion should be taken into account in skin friction determination for cohesive soils.

In 1981 [10], although not focusing on the soil-solid interfaces, the topic of cohesive soils in residual strength and its shearing behavior with a ring shear apparatus was introduced. There were four zones of shearing according to the clay particle, void ratio, and the residual friction coefficient namely Turbulent, Transitional, Sliding, and S_1 zone. The first three shearing modes were believed to be a soil-on-soil shear behavior, whereas the S_1 was a possible sliding shear when soil was failed against a smooth interface.

In 1995, research of the soil-solid interface of the Mexico Clay and the behavior of static and cyclic loading of friction pile was carried out [11]. The clay condition was analyzed in two situations, which were in a remoulded and undisturbed state. The study established adhesion coefficient with its effect on Liquidity Index and introduced a fatigue factor, which was a ratio of cyclic shear stress amplitude with shear strength ratio, from the number of stress reversals that turned out to be equal to unity. Other than that, the research also found the effect of repeated loading which considerably degrades the strength and stiffness of the soil in dynamic test, and that the strength gain in the static interface-on-soil tests for remoulded sample from consolidation would be less important.

In 2000, following the research in 1981 [10], the study of the clay-interface shear resistance with the ring shear apparatus on both the peak and residual strength was conducted [8]. The study concluded that different clay content would react differently with the interface roughness. The shear mode could change according to the roughness of the interface, which was evident in clays with low clay content.

In 2009, with the emerging studies of unsaturated soil, an unsaturated interface problem with the suction-controlled direct shear test was conducted on interfaces between unsaturated low-plasticity fine-grained soils and rough to smooth stainless steel counterfaces [12]. The experiments were done on a modified direct shear apparatus which accommodate suction in the tests. The study concluded that matric suction and net normal stress only had an influence on peak strength, whereas it became negligible at post-peak strength due to the disrupted air-water menisci. In addition, it was known that the effect of cohesion from the soil was bigger than adhesion in the shearing behavior.

In the same year of 2009, the effect of water content, normal stress, and rough surface on the shear stress-shear displacement relationship of clay-concrete interface were analyzed [13]. The experiments were conducted using ring shear, ring simple shear, cylinder shear, pull-out, and simple shear apparatuses.

The study found the interface shear behavior was different after a certain clay fraction for the direct shear and simple shear results for the rough concrete, whereas it stayed the same for the smooth surface. In addition, it was known that increasing the water content may change the interface failure mechanism.

In 2014, a study then presented the results of an experimental study on the interface shear behavior between Leda clay and steel [14]. The tests were done with simple shear test in Consolidated-Drained and Consolidated-Undrained conditions, which were defined with the shearing speed of the test. The study leads to several conclusions, such as the increase of interface roughness would lead to the increase of friction angle even though it will result in more interface contraction, the increase of the clay's dry density on the dry side of the optimum water content would increase the interface contraction which would enhance the shear strength happening at the interface, and the chemical treatment for the problematic soil would be a sound choice due to the increased friction resistance of the clay when the pore water salinity increases.

In 2018, a research was conducted to know the effect of interface roughness and unloading effect on the interface shear mechanical properties through the large direct shear test and a series of normal unloading stresses with three different structural interface roughness and unloading on the interface shear strength, interface shear modulus, and the interface shear dilatancy [15]. The study gave some conclusions: the interface shear strength increases with the increase of roughness until a maximum point of critical roughness, the concept of residual shear strength ratio (f_r) was introduced and the conditions were divided into three sections according to the unloading conditions, and the maximum value of shear dilatancy presented a positive relationship with interface roughness for the same residual load ratio.

Also in 2018, a study defined the properties of the interface for a future numerical simulation of the behavior of clayey soil reinforced with granular column [16]. The tests included a direct shear test of clayey soil and granular sand interface and a numerical model with finite-difference using FLAC3D. The results stated that both cohesion and friction angle was evident with a value in the range of the original clay and sand shear strength and that the FLAC3D simulation could reproduce similar behavior of the interface with its elastic-perfectly plastic model.

In 2019, an analysis of structural deformation and the interaction of interface between soil and structure was done to understand the mechanical shear properties of interfaces [17]. The tests consisted of using the direct shear with different water content of clay and four different kinds of water-cement ratio of the cement paste as the interface. The study concluded that internal friction angle would decrease as the water content increases and be stable at around 20 – 25% of water content, whereas the cohesion would first increase until the peak of 17% water content and would decrease afterward. As for the water-cement ratio, it was known that the different water-cement ratio would affect the roughness of the surface, which then leads to a bell-shaped distribution correlation with both the friction angle and cohesion of the interface shear strength.

Also in 2019, a unique interface test was done between a compacted natural clay and hemp fibers which were focused on three main parameters: compaction water content, type of interface test, and drainage conditions rate of loading [18]. The tests done were the Direct Shear Test and Pull-Out Test on a compacted clay with hemp fibers. The study concluded that there were minimal differences between the undrained and drained condition testing of the interface due to the partial drainage that occurred, the fast-rate test gave a bigger pull-out resistance than the slowly consolidated specimen, and that the pull-out test was more reliable than the direct shear test in undrained condition but were both satisfactory on the drained condition.

To summarize this section, a time-table of the development in soil-soil and soil-solid interface shear strength experiment can be seen in Figure 1. It can be seen that throughout the time, there were several developments that had been made, such as the different phrasing that was once skin friction was changed into interface shear strength, the different type of construction materials were differentiated into different surface roughness from the same materials, the type of soils expanded into problematic soils, the concept of unsaturated soil was incorporated into the interface, and the latest materials were not only interfaced with construction materials but also to different soil type or fibers.

1961	•Skin friction of different types of soils and construction materials •Four major controlling points were determined
1981	•Shearing behaviour of cohesive soils •Four typical particle shearing behaviour on peak and residual strength
1995	•Soil-friction pile interface in cyclic and static loading condition
2000	•Clay-interface shear strength at peak and residual strength on different roughness
2009	•Unsaturated soil interface shear strength behaviour •Effect of different tests on water content, normal stress, and rough surface of clay-concrete interface
2014	•Sensitive slay-steel interface in Consolidated-Drained and Consolidated-Undrained conditions
2018	•Unloading effect and interface roughness on clay soil •Clayey soil and granular column (modelled with sand) interface and numerical modelling with finite difference
2019	•Interface shear strength behaviour of soil and water-cement ratio rough surface •Clay-hemp fibres interface shear strength behaviour

Figure 1. Time-table development of the interface shear strength experiments of soil-on-soil and soil-solid interfaces

3.3. Incorporating Interface Shear Strength in Slope Stability

As previously stated at the introduction of this paper, several landslide cases happened at the interface of different strength soil of a slope. This leads to the importance of understanding the interface shear strength and its behavior in slope stability analysis. From the previous section, it is known that the development of the interface shear strength experiments varied greatly in the soil or solid material types, yet only a little works of literature were found for the slope stability interface. This section will give two examples of a study about interface shear behavior experiment that was taken from a slope stability case.

A study in 2013 analyzed the effect of degree of saturation on shear behavior of an interlayered soil-rock interface in the Baihetan site, where the soil sample was taken from one of the slope in the project [19]. The test included a multi-stage and single-stage direct shear of a recreated model from a concretesampled soil-concrete as the model of the interlayered weak zone soil stratigraphy from the site. The study concluded that from the successful single-stage direct shear, the cohesion took a greater effect on this interlayered weak zone rather than the friction angle and that the rougher the interface would give a higher shear strength. Although the study was not entirely based on a slope stability failure, the stratigraphy of the study was based on a slope in the Baihetan site, which gives a great connection on how the interlayered zone of the soil and rock at the site interact at the interface.

In 2017, another study was conducted from the model of Japanese great earthquake-induced slope failure [3]. The research was done in residual condition for kaolin clay with different cement percentage. The study tried experimenting on different cement in one layer soil, two-layer soil (soil-soil interface), different shear rate, and curing time of the cement for the constructed soil sample. The test used the ring shear test for the determination of the interface shear strength since they used the remolded soil. The results gave a several conclusions, such as the residual strength of cemented kaolin at cement greater than 2% was independent of the shear rate, residual friction angle of two-layer cemented-non-cemented was lower than pure kaolin, residual friction angle for the cemented kaolin was bigger than the non-cemented, at the cement ratio of up to 2%, the stress ratio of cemented kaolin increased as shear displacement increased, beyond that the stress ratio was not significant. From the conclusion, it was not clear whether the interface has an effect on the earthquake-induced slope failure that the case was modeled from. Yet, it can be briefly seen that it is possible to conduct a soil-on-soil interface of different strength type of soil based on the different cementation percentage of the clay, which gives a breakthrough on analyzing slope failure at the interface as a soil-on-soil interface experiment.

Although not explicitly defined, the two examples in this section provided an example of modeling the case of slope stability for heterogeneous soil stratigraphy into an experiment of interface shear strength. Thus, it could be concluded that the interface shear strength experiment can explain the shear behavior happened at a slope of different strength materials, giving an insight on understanding the slope failure mechanism due to failure at the interface.

4. Conclusion

A summary of the development in the soil-soil and soil-solid interface shear strength behavior from several works of literature were discussed. In addition, an example of applying the interface shear strength test for a slope stability case was presented. Thus, it can be concluded from the review that:

1. The commonly used interface shear strength tests are the simple shear test, direct shear test, and ring shear test. The rate and displacement of the test could also affect the results, which is why researchers should be careful in determining the rate and displacement when conducting the test.
2. Several changes have been made throughout the year of soil-soil and soil-solid interface experiments until the present, such as the term of skin friction changes into interface shear strength, the construction materials are changing according to the needs of cases in the present, the type of soils have expanded into problematic soils, and the type of interface has expanded to not only construction materials but also granular columns and even hemp fibers.
3. Examples of slope stability case modeled as interface shear test were discussed and gave an insight that it is possible to understand the shear behavior of different materials interface of a slope. As the number of research for this interface behavior is still limited, a further study in understanding the interface shear behavior modeled from a slope can be improved.

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