Abstract

Experimental and numerical study on pull-out resistance of flip-type earth anchors under different ground conditions, and its application to slope stability

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This thesis presents experimental and numerical studies on pull-out resistance of flip anchors (percussion anchors). A series of pull-out experiments were conducted using actual or model flip anchors. To take into account the unique feature of flip anchors that the anchor head rotates and opens in the ground, three installation conditions, which are Opened, Closed, and Driven, were prepared in sand grounds. Comparing the results of pull-out resistance of flip anchors under each installation condition on sand grounds, differences from ordinary pre-embedded plate anchors were able to be examined.

In a full-scale pull-out experiment in a field of clay ground, only Driven condition, which is a practical way to install the anchors, was prepared. An estimation method of pull-out resistance of flip anchors in clay was proposed based on the experiments.

Not only the pull-out resistance, but ground failure patterns with an uplift of a flip anchor in a plane strain condition were observed and compared with previous studies on plate anchors. The two-dimensional model was extended to three-dimensional model to estimate pull-out resistance of flip anchors on sand grounds. Based on the model, estimation methods of pull-out resistance of flip anchors were proposed. Moreover, an estimation method using finite element method (FEM) was also proposed, and calculated values from both methods were agreed well with those of a typical empirical estimation method for plate anchors.

An application of flip anchors for slope stability was also investigated by experimental and numerical study in this thesis. Flip anchors are found to be effective for slope stability.

Abstract

Anchors have been widely used for supporting structures on the ground and on the water. Anchors that are installed in the soil are largely called earth anchors or ground anchors. Anchors can be broadly divided into those that are used with grout and those that are not. There are 2 types of anchors among the anchors installed without grouting. One is pre-embedded in the ground and another is driven directly into the ground.

A typical pre-embedded earth anchors are plate anchors. The plate anchors are pre-embedded in the ground and are expected to have pull-out resistance due to the bearing resistance of the plate. The earth anchors can be used for a wide variety of purposes, such as embankment reinforcement, retaining wall reinforcement, tower support, and so on.

Among those anchors that are directly driven into the ground, there are percussion anchors which are rotate and open in the ground when tensile force acts. Percussion anchors are called “flip anchors” in this study. Unlike grouted ground anchors and plate anchors, flip anchors do not require curing period of grout. And because grouting is unnecessary, cement, water, and related equipment are not required. The required machines and resources are limited; thus, it is possible to respond immediately in the event of disasters. In addition, dust and muddy water accompanied with drilling and grouting are not generated. Flip anchors minimize the efforts and time required for installation and are environmentally friendly. Flip anchors have many advantages and have been used mainly in Europe, the United States, and Australia.

Although the workability is better, there are only a limited number of references directly referring to flip anchors. Moreover, there are still no popular design guidelines such as those found on ground anchors and soil nails. That makes further field application of flip anchors difficult. Even so, there are many studies that can be used for the study of flip anchors, including those of plate anchors. However, as a major premise, it is necessary to confirm that the flip anchors really behaves like the plate anchors after sufficiently open in the ground.

Thus, in this study, pull-out experiments of flip anchors similar to those of the plate anchors were carried out under the condition that the characteristics of the flip anchor to open in the soil were taken into consideration. Three installation conditions, such as “Opened”, “Closed”, and “Driven” were prepared to simulate a practical installation condition of flip anchors. And the experimental results conducted under these conditions can also be compared with those of plate anchors.

In laboratories, pull-out experiments on dense dry sand ground were conducted. Three-dimensional pull-out experiments using actual flip anchors, and two-dimensional pull-out experiments using model plate or flip anchors were conducted. In the two-dimensional vertical and diagonal pull-out experiments on the model dry sand ground, in addition to the relationship between pull-out force and pull-out displacement, the displacement of soil particles during the experiments was observed by photos during the experiments to model ground failure pattern.

Full-scale vertical pull-out experiments using actual flip anchors in fields were conducted on a sand ground and a clayey ground. From the results of the field experiments and ground failure patterns observed in the laboratory experiments, 3D ground failure patterns were modelled to estimate pull-out resistance of flip anchors in sand.

In addition, to investigate the slope reinforcement effect of flip anchors, a loading experiment on the model slope was conducted using model plate anchors in a plane strain condition or actual small flip anchors in a three-dimensional condition.

The pull-out experiments performed on the sandy ground was also simulated by numerical analysis using FEM. Through the series of experiments and numerical analysis, estimation methods of pull-out resistance of flip anchors by limit equilibrium method and FEM analysis were proposed.

In sand, pull-out resistance F_{max} of flip anchors increased as projected area of an anchor A increased; whereas, maximum pull-out pressure p_{max} of the flip anchors increased as A became smaller. F_{max} of Driven and Closed anchors, which are corresponding to the practical installation of flip anchors, reached about 80 % of that of horizontally embedded plate anchors (Opened anchors) within the experimental conditions in this study. Pull-out displacement w required for the flip anchors to attain F_{max} was the same amount as a length of an anchor plate L or about 1.5 times that amount.

Ground failure pattern in the pull-out experiments was simply modelled based on the observations of ground deformation during the pull-out experiments in a plane strain condition. F_{max} calculated from the proposed model qualitatively agreed well with measured F_{max} of each pull-out condition. The ground failure pattern of the flip (plate) anchors changes from “shallow anchor” model to “deep anchor” model at critical embedment ratio $(H / L)_{cr}$: where H is an installation depth of an anchor and L is a length of an anchor plate. Thus, the 2D ground failure model was extended to 3D ground failure models for a “shallow anchor” or “deep anchor”, respectively.

Using the limit equilibrium method (LEM) based on the 3D models and finite element method (FEM), pull-out resistance of flip anchors in sand were estimated. The calculated values of F_{max} were compared with the measured values of field experiments and calculated values based on the empirical method using breakout factor f_q. The calculated values of F_{max} based on the three estimation methods were all agreed well with each other. Furthermore, the calculated values were agreed well with measured values of F_{max} in the field experiments. The both estimation methods based on the 3D models and FEM could be promising ways to estimate F_{max} of flip anchors in sand, as long as the w required for a plate anchor sufficiently opens is taken into the consideration for H/L.

In clay, pull-out behavior of flip anchors is quite different from that in sand. In clay, F_{max} of a flip anchor was proportional to A. This indicates that p_{max} acting on the anchor head was equivalent regardless of A. As an estimation method of pull-out resistance of flip anchors in clay, the interpretation method for T-bar penetration test is applied. It is because pulling a flip anchor throughout clay is just reverse way of pushing T-bar into the clay. The predicted p range estimated from the values of undrained shear strength of the soil c_u from the vane shear tests and bearing factor of T-bar N_b of 10.5 agreed well with the measured p range of the field experiment. Thus, the estimation method based on the interpretation of T-bar penetration test could be a promising way to estimate pull-out resistance of flip anchors in clay ground.

Finally, an application of flip anchors to slope stability was verified by experimental and numerical study using FEM. From the results of the loading experiments on the shoulder of the model slope ground, flip anchors were found to be effective for slope stability as well. The results of the experiments well agreed with the FEM simulations using the Mohr-Coulomb model. Not only the reinforcement effect but also the displacement of the ground and tensile force acting on anchor rods can be well obtained by FEM analysis. Thus, reinforcement effect of flip anchors can be analyzed by finite element method. In the case of slope reinforcement, the dilatancy of the soil greatly affects the reinforcement effect.

In the scope of this study, the pull-out resistance of flip anchors installed at various grounds conditions, angles, and depths has not been all investigated. From this study, it was found that the research of pre-embedded plate anchors can be employed in the design of flip anchors, as long as the displacement of flip anchors to open are taken into consideration. Thus, for the conditions that could not be verified in this study, a number of studies on plate anchors, which are performed under other conditions, can be effectively utilized for flip anchors.

Construction of flip anchors can be designed by FEM, but the analysis results are greatly affected by the parameters, thus it is necessary to accurately consider the effects of the parameters for field application. Especially in the case of slopes, the setting of the dilatancy angle has a great influence. In this study, the shoulder of the slope is loaded to analyze the slope stability, but for practical purposes, the effect of flip anchors on slope stability should also be verified using the shear strength reduction (SSR) method.

Although the results of this study were obtained under limited conditions, this study complements the research of plate anchors, and are expected to contribute to the further field application of flip anchors.

令和　3年　8月　2日

学位論文審査報告書（甲）

1．学位論文題目（外国語の場合は和訳を付けること。）

Experimental and numerical study on pull-out resistance of flip-type earth anchors under different ground conditions, and its application to slope stability

（フリップタイプアースアンカーの引抜き抵抗力に関する実験的および数値解析的研究と斜面安定への適用に関する検討）

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3．審査結果の要旨（600～650字）

本申請論文に対して、令和3年5月26日に学位論文審査員による口頭試問を行い、論文の内容について精査した。また、令和3年8月2日に開催した口頭発表および同日に開催した審査委員会において協議した結果、次のとおり判定した。

フリップアンカーは、矢尻形状の閉じた状態（closed)のアンカープレートを貫入ロッドを介して地盤に打込んで設置する。アンカーには、ロッドあるいはワイヤーが取り付けられており、これらに引張り力が作用すると、アンカープレートが引き上げられながら回転し、開いた状態（opened)になり、アンカープレートに作用する土圧によって、引張抵抗を発揮する。従来のアンカーのようにグラウトを行わないため、フリップアンカーは迅速に施工でき、すぐに引抜き力が発揮されるため、比較的小規模な斜面安定対策に有効であると考えられる。しかし、フリップアンカーの適用実績はほとんどなく、設計法も確立されていない。申請者は、まず、砂地盤、粘土地盤において、アンカー寸法、設置深さ、アンカープレートの設置方法（埋込み、打込み、opened or closed）を変えて、引抜き実験を実施した。続いて、フリップアンカーの引張抵抗メカニズムや地盤破壊状況を詳細に調べるために、透明な土槽内を用いて2次元（平面ひずみ条件）で模型アンカーの鉛直方向、斜め方向の引張実験を実施した。さらに、実験のFEMシミュレーションを実施した。これらの結果に基づき、フリップアンカーの引張抵抗力の評価方法を提案した。引続き、フリップアンカーによる斜面補強に関する模型実験とそのFEM解析を実施し、フリップアンカーによる斜面補強効果を検証した。申請者の研究成果は、フリップアンカーの実務への適用に大きく貢献したと評価できる。以上より、本学位申請者（吉田翔太氏）は博士（工学）に値するものと判定した。

4．審査結果　(1) 判　　定（いずれかに○印）合　格・　不合格

(2) 授与学位　博　士（　工学　）