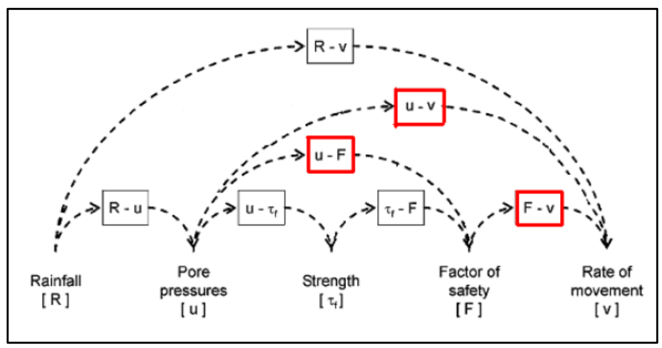
**Mechanism, Modeling and Forecasting of Landslide Displacements, Grant No: 249186, FOLADIS**

Landslides cause significant damage and loss of life throughout the world. There is an increase in landslide activity as a result of continued deforestation, increased construction in landslide-prone areas, and increased regional precipitation by changing climate patterns, which is a primary trigger for landslides. One of the four priorities areas in FP7 have been identified as triggering factors and forecasting, and mitigation strategies for natural hazards.

Although they do not typically cause loss of life, slow landslide movements can severely damage structures, interrupt the serviceability of lifelines, highways, railways, waterways, and pipelines; and, related stabilization efforts can be too costly. Most of these slow-moving landslides are in cohesive soils and caused by rainfall induced high ground water pressures. Significant progress have been made in understanding the mechanism of such landslides (Leroueil 2001, Picarelli et al. 2004) as well as forecasting methods (Crosta and Agliardi 2003, Corominas et al. 2005, Petley et al. 2005) and the relation of the degree of stability to the rate of movements (Bonnard and Glastonbury 2005, Calvello et al. 2008, Huvaj-Sarihan 2009). The general framework of the relationships between various parameters are shown in the figure below.

**Project objectives:**




The overall goal of this research is to reduce damage and loss of life caused by landslides, by increasing our understanding of the mechanism of landslides, and modeling and forecasting techniques. The specific objectives of the research are:

1) to identify the triggering factors and failure mechanisms in landslides composed mainly of (or dominated by) cohesive soils,
2) to investigate application of numerical models in slope displacement analyses and calibration of model parameters by observed deformations in well-documented case histories.
3) to establish threshold slope displacement rates that can be used in setting up alarm levels and early warning, and to improve forecasting methods and tools that would help predict the time of a possible catastrophic landslide,
4) to transfer the knowledge to end-users including practising engineers by preparing handbooks/guidelines and training courses.

**Work Packages and Results:**

**Work Package 1.2.** Selection of landslide case histories with detailed material properties, the pore water pressure measurements and records of slope displacements with time.
**Work Package 2.1.** Prediction of landslide displacements by using finite element method.
**Work Package 3.1.** Analyses of relation between groundwater level, factor of safety and rate of movement.
**Work Package 3.2.** Determination of threshold deformation rates from laboratory tests
**Work Package 3.3.** Forecasting of failure time based on the measured displacements of the slopes.
**Work Package 4.1** Dissemination of information

To identify the typical triggering factors and failure mechanisms, landslide cases in the literature, in natural or man-made/cut slopes, that are mainly composed of (or dominated by) cohesive soils, was collected from Turkey, other European countries and from around the world. The information on the geology, hydrogeology, failure mechanism, slope geometry, characteristics of rupture surface, geotechnical index and shear strength properties of the materials involved, and monitoring and deformation behavior of various slow moving reactivated landslides were collected.

These reactivated, slow-moving landslide case histories with extensive pore pressure and movement data are further analysed. For these landslides, the relation between pore water pressures, factor of safety and rate of movements of the slide are investigated by using limit equilibrium and finite element methods. It is found that there is a nonlinear relationship between these three variables. Sensitivity of slow moving landslides to changes in pore water pressure is developed by defining the percent change in factor of safety and percent change in pore pressure coefficient ru, for 10-fold change in velocity. Such relations could especially be useful in planning required level of remediation, for example, to decide on how many meters the ground water level should be lowered at a certain pore water pressure measurement station, so that the slope stability increases to a desired level of factor of safety, and movement rates are reduced to an acceptable slow rate.

The results will be useful to assess the changes in the degree of stability of a slope, and its correlation with expected slope displacement rates. This can also be used in setting up alarm levels and early warning such as “extremely slow/creep deformation rates (<16 mm/year) = No action” to “unacceptable displacement rates = Danger/Alarm” etc. Based on an extensive literature search on landslides, in addition to laboratory creep movement measurements, typical creep rates that is occurring in all slopes composed of clayey soils are determined to be on the order of 2-50 mm/year. The results will also be useful for evaluating the existing condition of slopes and deformation rates, and also for stabilization purposes.

To investigate failure time prediction methods and to establish threshold deformation rates in slopes of cohesive soils, stress-controlled laboratory direct shear and ring shear tests are investigated. Stress-controlled tests are very important because it is the governing mechanism in real-life slopes, i.e. the slopes are sitting under a certain normal and shear stress level, they are deforming with time under constant stress conditions, or they are deforming with changes in environmental and in stress conditions. The results of laboratory tests is integrated with the numerical methodology and will lead to a reliable threshold displacements to be used in practice.

For the failure time prediction of slow moving landslides, the velocity and acceleration of slope movement is used. The accuracy of failure time prediction methods as well as their range of prediction/sensitivity is studied. The enhancement of forecasting methods plays a crucial role in reducing the damage and loss of life related to landslide hazards.

The results from this project should lead to establishment of threshold slope displacement rates that can be used in setting up alarm levels and early warning, and to improve forecasting methods and tools that would help predict the time of a possible catastrophic landslide. Such tools would help protect the people from the possible consequences (damage and death) of natural hazards. The results of the project will help create a better understanding of the physical phenomenon of landslides, an early warning system against landslides, and a trained public that is more aware of landslide issues.

**Dissemination of the project outcomes:**
This work package involves dissemination of the project deliverables via training courses, workshops and a web site. Some of the dissemination works are presented here. Two M.S. degree students (Bora Gundogdu and Arash Maghsoudloo) were trained; these students finished their thesis. Results of the project were presented at national and international conferences by the researcher and by the graduate students. Short courses were given on landslides to Chamber of Civil Engineers (IMO) in Turkey, to METU undergraduate civil engineering students as part of their first year freshmen introductory course, and to third year undergraduate students as part of their summer practice, also field trips to landslide sites near Ankara, Turkey, were organized for students. A new undergraduate course (CE4004 Shear Strength and Slope Stability) is created at Middle East Technical University, Civil Engineering Department, which was approved by the Faculty of Engineering and it is offered every Fall semester since the Fall semester of 2010. Recently in 2013 this undergraduate course is also offered at METU Northern Cyprus Campus. In this undergraduate elective course, the students were taught about landslides and slope stability analyses methods, then they were given specific landslide cases and were required to analyze these and develop slope stabilization alternatives. In 2013 a team composed of two undergraduate students (Berkin Dortdivanlioglu and Ozgun Alp Numanoglu) from METU competed in an international competition organized by ASCE GeoInstitute to predict the groundwater level at the time of failure of a landslide. These students were supervised by the researcher and they ranked 3rd in the competition. A seminar was given to about 200 villagers at Karabuk organized by the local Disaster and Emergency Management Presidency (Karabuk Afet Isleri AFAD), the villagers were informed about landslides. For the dissemination of project results a website was established.

The project website is*:* **www.metu.edu.tr/nejan/FOLADIS**

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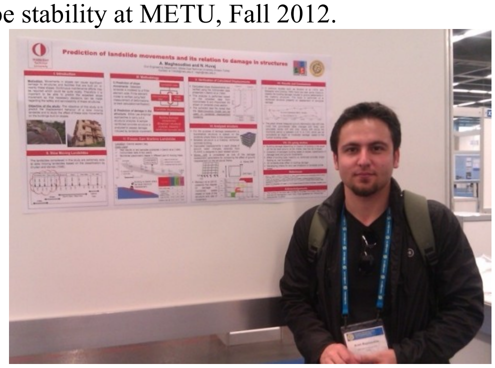
With Bora Gundogdu at Mountain Risks International Conference, Florence, Italy, November 2010

With students at Babadag landslide (at the back) in Turkey, 2010

With students who are taking the new course on landslides and slope stability at METU, Fall 2012.

With Bora Gundogdu at European Geosciences Union, 3-8 April 2011 at Vienna Austria




Arash Maghsoudloo at EGU at Vienna, 2012


With Arash Maghsoudloo at M.S. Thesis defense, 2013

With undergraduate students Berkin Dortdivanlioglu and Ozgun Alp Numanoglu, who ranked third at "Geoprediction" competition of ASCE GeoInstitute, San Diego, March 2013.

With students at a landslide near Ankara, Summer Practice, 2011