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ORIGINAL PAPER

Surface displacements of two landslides evaluated by GPS and inclinometer systems: a case study in Southern Apennines, Italy

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Abstract This paper reports experimental data on surface and deep displacements evaluated by means of GPS stations and inclinometers in two rototranslational deep landslides in a clayey slope of the Italian Southern Apennines. The displacements of the landslides cause continuous damage to buildings and infrastructures. To study these phenomena and control their effects, the local public administration provided financial support for a geotechnical investigation that started in 2004. Laboratory tests, in situ pore pressure and inclinometer measurements were carried out. In July 2006, systems of fixed-in-place inclinometer probes with continuous data acquisition were installed in two of the eleven guide casings, in correspondence to the slip surfaces detected by previous periodical measurements. In the meanwhile, a GPS network was installed, consisting in six permanent stations and ten non-permanent ones. Among the latter, five were installed on the top of five inclinometer casings. The experimental results show that, in the case under study, the surface displacements evaluated by means of the GPS stations are consistent with the surface displacements evaluated by means of the inclinometer measurements. This implies mutual data validation, availability of considerable amount of continuous data, as well as monitoring continuity when, for some reason, one of the instruments goes out of use.

Keywords Landslide · Displacements · Inclinometer probe · GPS · Varicoloured Clays

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1 Introduction

The two landslides under examination occur on the slope of a hill facing the valley of the Basento river, East of the town of Potenza, in Southern Italy (Figs. 1, 2). Several geological and geomorphological studies have been carried out in the last 30 years (Guida et al. 1988; Perrone et al. 2004; Del Prete and Del Prete 2009; Di Maio et al. 2010). As the number of boreholes and monitored zones increased, the landslide description progressively changed, as shown by Fig. 2, which draws both the former map by Guida et al. (1988) and the landslide boundaries of more recent investigations.

Fig. 1 Panoramic view of the two considered landslides pointing out the cross-section traces

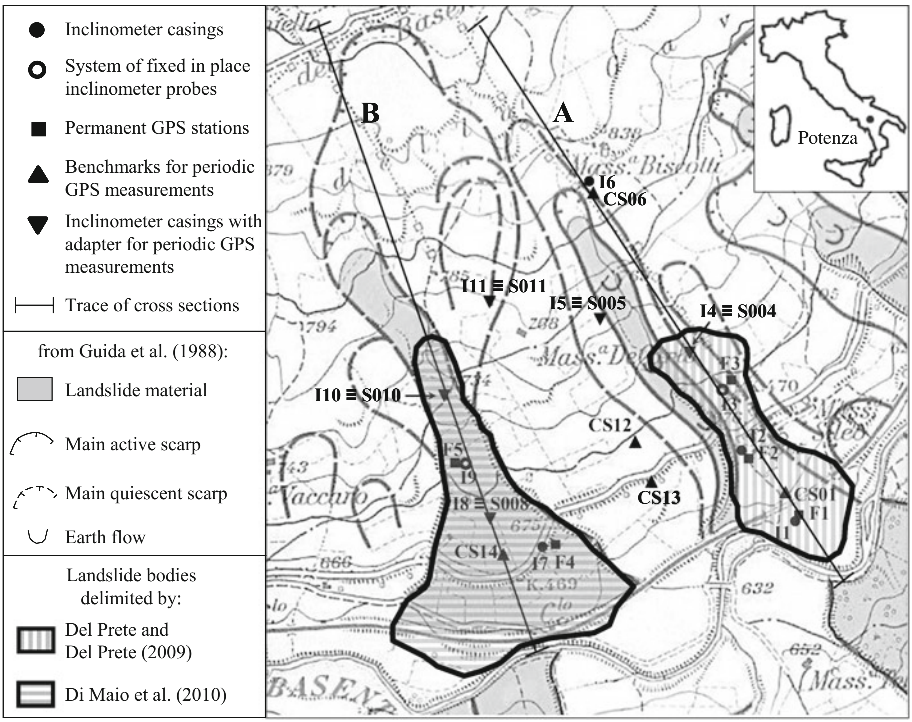


Fig. 2 Geological map redrawn from Guida et al. (1988) and boundaries of landslides A and B as defined by Del Prete and Del Prete (2009) and by Di Maio et al. (2010), respectively. The positions of inclinometer boreholes and GPS benchmarks are also shown

The landslides, which exhibit similar geometric and kinematic features, occur in the geological formation of the Varicoloured Clays (Middle Cretaceous–Oligocene), constituted by tectonized, fissured and heterogeneous clay shales, clay and mudstones, including blocks and layers of marls, calcarenites and limestones (Pescatore et al. 1999). They can be described as ancient and complex rototranslational slides evolving into earth slides according to the classification of Cruden and Varnes (1996).

The slow movements of the landslides cause severe damage to houses and infrastructures. In particular, the highway and the railway, whose tunnel crosses one of the accumulation zones, need frequent maintenance and strengthening, besides continuous monitoring (by extensometers, inclinometers and topographic measurements), with noticeable social cost.

In order to study and to monitor the landslides, an office of the local public administration (Regione Basilicata) provided financial support for a geotechnical investigation. In 2004, 11 continuous coring boreholes were driven, each equipped with two Casagrande piezometers, or electrical piezometers, at the depths of about 15 and 35 m below the ground surface. In addition, 11 deep core-destruction boreholes were driven and equipped with inclinometer casings (Fig. 2). In 2006, fixed-in-place inclinometer probes, with continuous data acquisition, were installed in two of the eleven casings, in correspondence to the slip surfaces.

In the same period, a GPS network was also installed for the measurement of surface displacements by permanent and non-permanent stations. The project of the network was carried out by the Geological Survey of Italy—Geophysical Service (ISPRA—Institute for Environmental Protection and Research), in collaboration with the University of Basilicata—with the financial support of Regione Basilicata—and the National Civil Protection. In compliance with law no. 267/98, enforced after the disaster of the Sarno flood and mudflows in May 1998, a GPS monitoring network of several Italian landslides, including those of Costa della Gaveta, was funded. The GPS system was meant to complete the integrated monitoring system of rain, pore pressures, deep and surface displacements, so as to study the phenomena and eventually to give warnings to the population for disaster prevision (Calcaterra et al. 2008).

On the basis of experimental data, some important features of the landslides have been understood. Landslide B has been studied by Di Maio et al. (2010). It was understood to be an earth slide, whose displacements can be considered uniform in each investigated transversal section of the channel. The displacement rate decreases from upslope to downslope, probably because of the increase in the areas of transversal sections, the "soil discharge" being practically constant. Landslide A (highlighted in Fig. 2) has been analysed by Del Prete and Del Prete (2009); our current study seems to show that it is only a small portion of a much larger and complex landslide.

This paper deals with one of the many important aspects of the study of both landslides: that of displacement measurements. It reports the displacement profiles obtained by mobile and fixed-in-place inclinometer probes and the surface displacements obtained by permanent and non-permanent GPS stations. Furthermore, the paper shows the consistency of data obtained with different instruments and highlights the usefulness of the integrated system.

2 Inclinometer measurements

Eleven core-destruction boreholes, up to 50 m deep, were equipped with inclinometer casings in the two landslides under examination (Fig. 2). Standard inclinometer measurements started at the beginning of 2005, following the ASTM 2005 standards and the procedures suggested by Machan and Bennet (2008). Measurements were carried out along both the A and B axes, at depth intervals of 50 cm. To obtain cumulative displacement profiles, data readings were added from the bottom up, assuming fixed casing tip. The cumulative displacement obtained at 50 cm depth was considered as the surface displacement associated with inclinometer readings. A spiral probe was used to correct possible spiralling errors.

Figure 3 shows longitudinal sections of the landslides with cumulative displacement plots obtained in July 2006 (the last occurrence of standard inclinometer measurements in all the boreholes), which allowed to draw possible slip surfaces quite accurately. It is worth noting that these slip surfaces were confirmed by all the subsequent measurements.

The following step of the analysis was the evaluation of the rate of displacements. Periodical measurements by mobile inclinometer probe have the advantage of providing the profile of relative displacements along the whole casing length. However, being discontinuous in time, they do not allow for the evaluation of possible rate variations in short time intervals. On the other hand, fixed-in-place probes provide continuous data acquisition, but their installation along the whole height of inclinometer casings would be very expensive. In the case under examination, to maximize the advantages of both systems, once the slip surface was detected and the main kinematic characteristics of the landslides were understood, a few fixed-in-place probes were installed. Their positions were such as to give useful information to infer the entire displacement profile from the slip surface to the ground surface.

As an example, Fig. 4a shows the cumulative displacement profiles determined for borehole I9, drilled in the landslide B. In this case, as for most of our inclinometers, the profiles indicate an almost uniform displacement from the ground surface to the slip surface. In July 2006, three fixed-in-place probes were installed in casing I9. The central one was installed with its centre at a depth of 25 m and the other two above (20 m) and below it (30 m), respectively (as shown in Fig. 4b, c). Since then, the rotations are

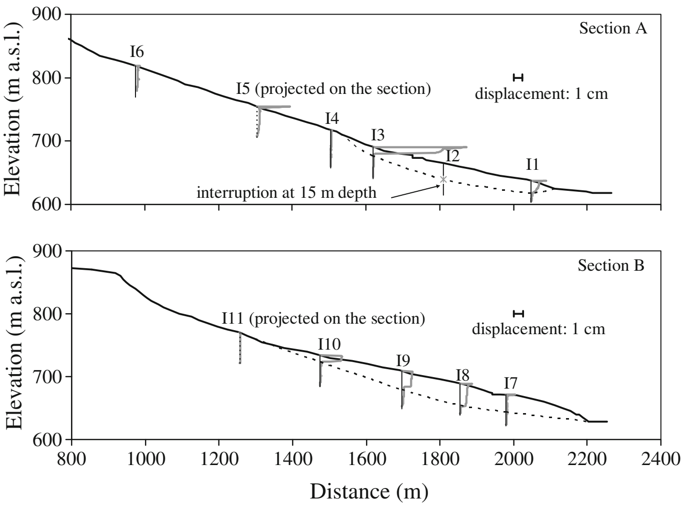


Fig. 3 Sections of landslides A and B with inclinometer profiles as of July 2006. Zero measurements were carried out in February–March 2005

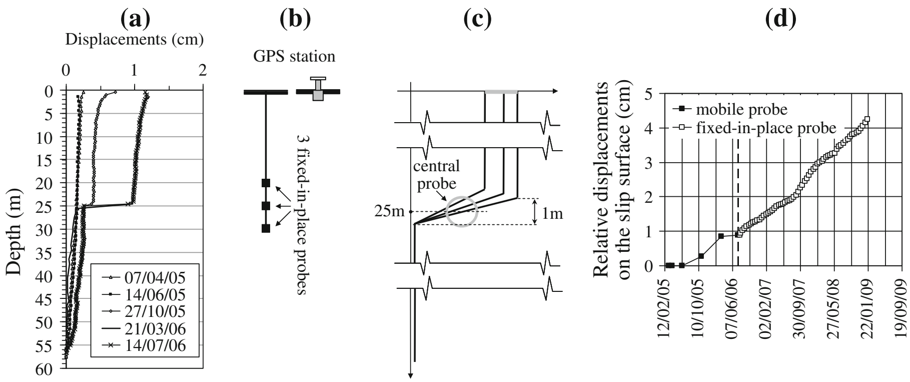


Fig. 4 Displacement profiles in I9 obtained by standard inclinometer measurements (**a**); scheme of the installation of fixed-in-place probes (**b**); scheme for displacement calculation (**c**); displacements versus time from mobile probe and then from fixed-in-place probe (**d**)

continuously monitored. As expected, the upper and lower probes registered almost constant inclination. To evaluate the displacements on the slip surface, the inclination registered by the central probe was attributed to a 1-m-thick band, as schematically shown in Fig. 4c. Figure 4d reports the displacements so obtained and shows that the rate of displacement is not constant. The possible causes of changes, currently under examination, include pore pressure variations and seasonal erosion at the toe.

Three more fixed probes were installed in I3, similar to I9. Unfortunately, probably because of an erroneous installation, the central probe gave rotations that were always oscillating around a constant value. Furthermore, in January 2009, the probes in I9 went out of use. Notwithstanding this, monitoring of the zones around I3 and I9 can continue thanks to the nearby GPS stations (F3 and F5, respectively), as shown in the next section (Fig. 7).

3 GPS measurements and comparison between GPS and inclinometer data

The GPS network consists of a sub-network of six permanent stations and a sub-network of ten non-permanent stations (Fig. 2). The former went in use in July 2007, the latter in July 2006. The position of the stations was decided after the evaluation of the displacement field by inclinometer measurements. Most of them were placed nearby the inclinometers.

The Master permanent station was installed in a stable area, upslope from the landslides. It consists of a dual frequency GPS receiver and a choke ring antenna, and its position is periodically controlled relatively to permanent stations of the EUREF network. The other five permanent stations (F1–F5), all located in the two landslides, are equipped with a dual-frequency geodetic antenna. Three of them are installed on columns (whose scheme and picture are reported in Fig. 5a, b), founded on a large concrete block (1.5 m deep) that prevents tilting. The other two are placed on rigid structures: a low concrete wall (F2) and a building (F4) with shallow foundations (about 1.5 m depth). Continuous data observations, stored at a 30-s sampling rate, are automatically transmitted by means of GSM modem to the processing centre of the ISPRA Geophysical Service. Here, the quality of raw data is controlled, RINEX files are created and the daily displacements, relative to the Master station, are provided as output. In particular, data are pre-processed by Leica GPS Spider

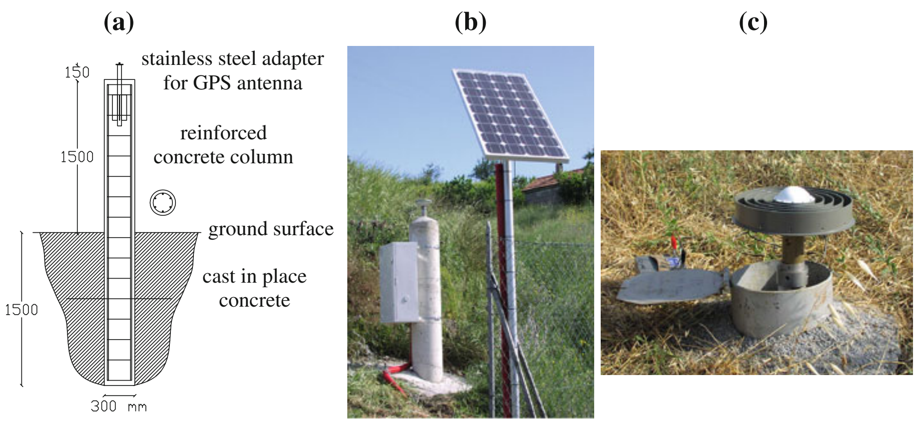
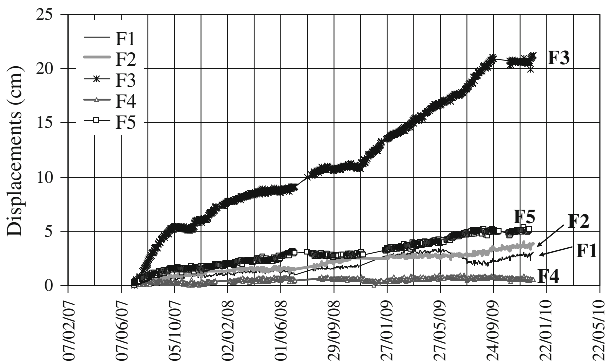


Fig. 5 Schematic section of a column for permanent GPS stations (**a**); pictures of a permanent GPS station (**b**); and of a non-permanent GPS station on the top of an inclinometer casing (**c**)

Fig. 6 Displacements against time of the permanent GPS stations



software and subsequently re-processed with Bernese 5.0 software. Figure 6 shows the horizontal displacements of the five stations between July 2007 and the end of 2009. On the basis of these data, the annual displacement rate ranges between 2 mm/year (in the B landslide) and 80 mm/year (in the A landslide). According to the classification proposed by Cruden and Varnes (1996), the landslide movements can thus be defined as extremely slow or very slow.

The GPS non-permanent stations were installed to fill in the network. Five of them were positioned on rigid structures: three (CS01, CS06 and CS12) on rigid walls, two (CS13 and CS14) on very low concrete walls. In all cases, the foundation is 1–1.5 m deep. The other five coincide with the top of five inclinometer casings, on which apposite mobile adapters (Fig. 5c) are positioned during measurements. This type of measurement was performed to evaluate whether surface displacements derived from inclinometer profiles are consistent with GPS displacements. After the first survey (zero-measurement) in July 2006, two further surveys were carried out, in November 2007 and September 2008. During the surveys, several geodetic receivers were employed, using a forced centring system in order to warrant the repetitiveness of measurements. Static positioning technique was used for the accuracy of the results, with three site occupations and at least six hours acquisition.

Data processing was performed using Bernese 5.0 software, and the coordinates of the stations were obtained by constraining some EUREF permanent stations with a processing strategy for regional GPS networks.

Summing up, with the exception of the non-permanent stations on the top of the inclinometer casings, GPS stations allow the evaluation of the average displacement of a surface soil layer 1–1.5 m thick.

The comparison between GPS displacements and surface displacements evaluated by inclinometers shows a quite good agreement (Figs. 7, 8), particularly between inclinometer and periodic GPS data relative to the top of the casings. It can also be observed that, in the case of inclinometer I3, GPS measurements kept giving information on landslide displacements when the inclinometer instruments went out of use. Although a complete model of the landslides has not been formulated yet, available data allowed for some risk mitigation actions. In fact, on the basis of the registered displacement trend, a pedestrian overpass near I3—which was evidently deforming—was removed. Furthermore, on the basis of data registered by inclinometer I10 first and subsequently by GPS station S010, both showing a sensible acceleration of displacements, a letter of warning for nearby buildings, which had already been severely damaged by previous movements, was sent to the local Civil Protection Office.

Figures 6 and 7 show that the rate of displacement undergoes slight variations with time. Recent studies (Vassallo and Di Maio 2008) show a possible correlation between displacements and precipitations. A mathematical model of the pore pressure distribution in the slope and of the relation between rain and displacements is currently under examination. First results seem to show that, due to the subsoil geometry and properties (in particular, quite low permeability), rain does not succeed in significantly influencing

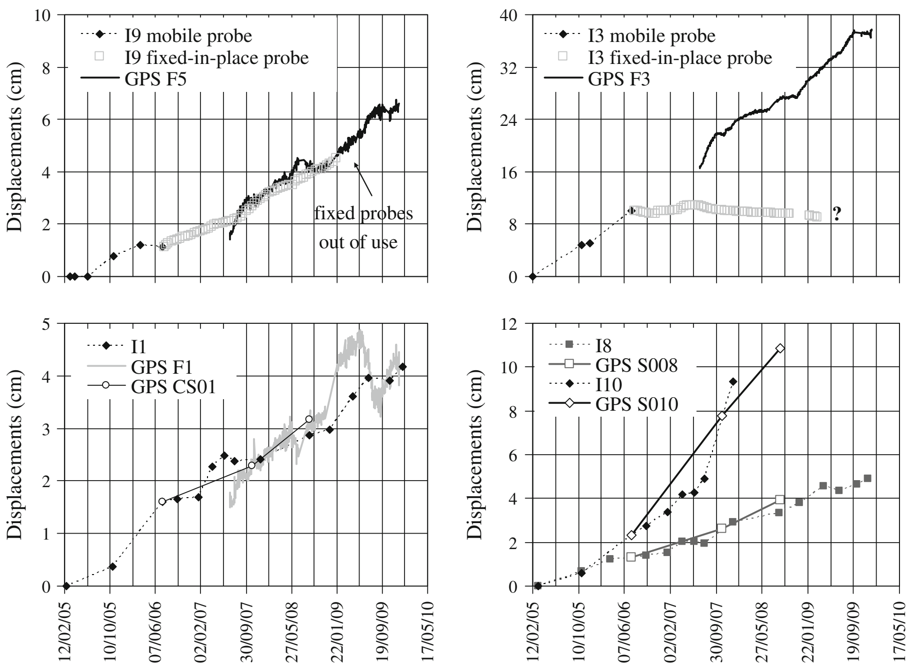


Fig. 7 Comparison among surface displacements obtained by different techniques

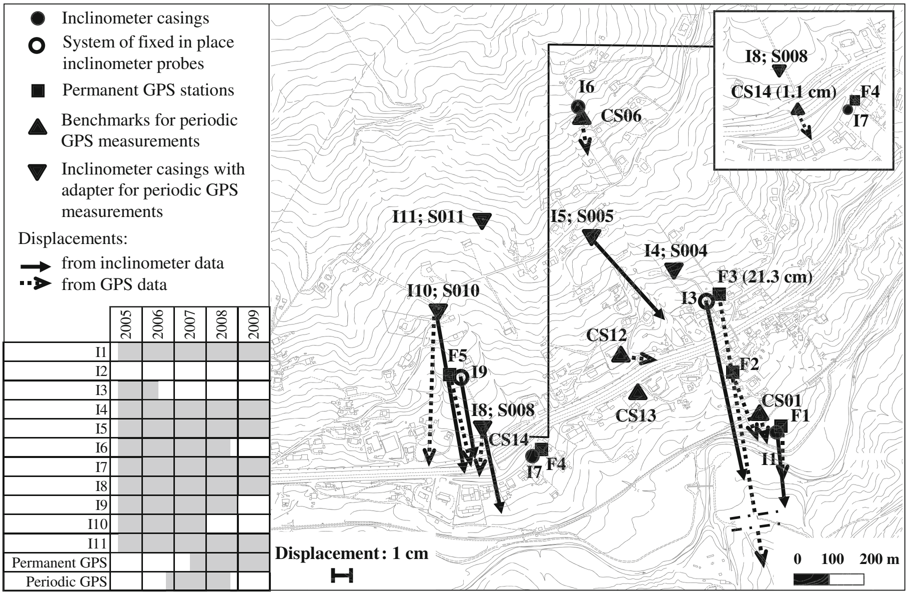


Fig. 8 Ground surface displacements obtained by inclinometers (Ii) and by GPS permanent (Fi) and non-permanent (CSi and S0i) stations. Only displacements greater than 1 cm are reported. The vector of CS14, otherwise covered by the other vectors, is reported in the magnification

pore pressures at the depth of slip surfaces (just as for other clay slopes, e.g. Kenney and Lau 1984; Leroueil 2001; Perrone et al. 2008; Di Maio and Vassallo 2010). Some other triggering factors must be investigated, such as erosion at the toe.

Finally, Fig. 8 compares vectors of ground surface displacements obtained by inclinometers with those evaluated by the GPS stations. Each vector was evaluated in the period specified in the table. The displacement of I9 was obtained using both mobile and fixed inclinometer probe data. A general good agreement can be observed concerning displacement direction.

4 Conclusions

The experimental results relative to this case history show the usefulness of an integrated monitoring system constituted by mobile and fixed-in-place inclinometer probes and GPS stations for surface displacement measurements.

Periodical measurements by mobile inclinometer probe provide the displacement profile along the whole casing length. However, they do not allow for the evaluation of a continuous time trend of displacements. On the other hand, for deep slip surfaces, the installation of fixed-in-place probes with continuous data acquisition along the whole height of inclinometer casings would be very expensive. In the case under examination, the deformations are concentrated in a thin zone. This allows a satisfactory monitoring of the landslide by a few fixed-in-place probes installed around the slip surface that was previously detected by periodical measurements, thus maximizing the advantages of both systems.

The usefulness of GPS systems in continuous monitoring of landslides is widely recognized (among others: Gili et al. 2000 and references therein; Malet et al. 2002). In our case, experimental results show that the surface displacements evaluated by the GPS stations in 3 years are consistent with the surface displacements evaluated by the inclinometers. Strictly speaking, the values of “surface” displacements evaluated by GPS and inclinometers could be different even if the bottom end of the casing is effectively fixed. In fact, the two systems consider different soil zones and interact differently with them. In addition, each system is affected by its own casual and systematic errors (Gili et al. 2000). In the case under consideration, GPS stations (installed either on the top of the inclinometer casings or on rigid structures) provided displacements consistent with surface displacements obtained by inclinometer profiles probably because these latter were very regular and almost uniform from the slip surface to the ground surface.

The consistency of the surface displacements evaluated with the different instruments in the same zone allows for continuous monitoring when, for some reason, one of the instruments goes out of use. Such a continuity is useful for the study of the landslides' triggering factors besides the detection of possible accelerations and consequent increasing hazards to the population.

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