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56	Abstract	This research pro- numerical mode landslides, appli earthflow (Dolom forward calculati calculations, the shear zones deli a detailed datas	pposes a conceptual approach for analysis and lling of the hydromechanical behaviour of large ed to one of the source areas of the Corvara nites, Italy). The approach consists of two steps: on and inverse analysis. For the forward geological model of the slope considering several mitating landslide units was developed, based on et of field investigation and monitoring data. A

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		zones. The transient distribution of pore water pressure in the slope was considered by means of an additional purely hydrogeological model. These results were used as averaged hydraulic boundary conditions in the calculation of stress and deformation fields with the continuum finite element method (FEM). The numerical model was then calibrated against ground surface displacement rates measured by D-GPS, by iteratively varying the material parameters of the shear zones. For this task, an inverse analysis concept was applied, based on statistical analyses and an evolutionary optimisation algorithm. The inverse modelling strategy was further applied to gather statistical information on model behaviour, on the sensitivity of model parameters and on the quality of the obtained calibration. Results show that the calibrated model was able to appropriately simulate the displacement field of the earthflow and allow the requirements, difficulties and problems, as well as the advantages and benefits of the proposed numerical modelling concept to be highlighted.
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Geomechanical assessment of the Corvara earthflow through numerical modelling and inverse analysis

12 Abstract This research proposes a conceptual approach for anal-13ysis and numerical modelling of the hydromechanical behaviour 14 of large landslides, applied to one of the source areas of the 15Corvara earthflow (Dolomites, Italy). The approach consists of two steps: forward calculation and inverse analysis. For the for-16 17ward calculations, the geological model of the slope considering 18 several shear zones delimitating landslide units was developed, 19based on a detailed dataset of field investigation and monitoring 20data. A viscoplastic constitutive model was used to describe the 21time-dependent material behaviour, i.e. the creep, of the shear 22 zones. The transient distribution of pore water pressure in the 23slope was considered by means of an additional purely 24hydrogeological model. These results were used as averaged hy-25draulic boundary conditions in the calculation of stress and de-26formation fields with the continuum finite element method (FEM). 27The numerical model was then calibrated against ground surface 28displacement rates measured by D-GPS, by iteratively varying the 29material parameters of the shear zones. For this task, an inverse 30 analysis concept was applied, based on statistical analyses and an 31 evolutionary optimisation algorithm. The inverse modelling strat-32egy was further applied to gather statistical information on model behaviour, on the sensitivity of model parameters and on the 33 quality of the obtained calibration. Results show that the calibrat-34 35 ed model was able to appropriately simulate the displacement field 36 of the earthflow and allow the requirements, difficulties and prob-37 lems, as well as the advantages and benefits of the proposed 38 numerical modelling concept to be highlighted.

40 Keywords Finite element method · Numerical

41 modelling · Corvara earthflow · Dolomites · Italy

#### 42 Introduction

39

In Italy, a number of large-scale and deep-seated complex landslides, including earthflows, affect the Alps and the Apennines (Guzzetti et al. 1994; Trigila et al. 2010). They can be up to 50 m deep and can cover several square kilometres. In the affected regions, this represents a major socio-economic problem, as landslides may cause continuous damage to infrastructures and, in several cases, they pose a potential threat to settlements.

50 Since few decades, numerical modelling has been applied to 51 earthflows by various authors using different approaches, with the 52 aim of better understanding landslide evolution (Picarelli et al. 1995; 53 Angeli et al. 1996a, b, 1998; Vulliet and Bonnard 1996; van Asch et al. 54 2007; Comegna et al. 2007). In some case, the objective of the 55 numerical modelling was to assist the design of effective technical 56 countermeasures (Borgatti et al. 2007a; Marcato et al. 2009, 2012).

57 A manual trial-and-error procedure is often adopted to cali-58 brate the numerical slope model against observed displacements. 59 Alongside this approach, which is strongly based on expert knowl-60 edge, the application of inverse analyses for the calibration of 61 numerical models is an appropriate concept for the identification 62 of parameters that cannot be easily determined directly from laboratory experiments (Hvorslev 1949). Inverse analysis is widely 63 used in many engineering fields such as hydraulics, damage anal-64 ysis and structural dynamics. A variety of different optimisation 65 schemes and algorithms are available from literature. In recent 66 67 years, due to the availability of faster computer hardware, inverse parameter identification strategies and optimisation procedures 68 have been more and more frequently used also in engineering 69 geology and geomechanics by many authors (Gens et al. 1996; 70 Ledesma et al. 1996a, b; Zhang et al. 2003; Calvello and Finno 712004; Malecot et al. 2004; Feng et al. 2006; Finsterle 2006; Meier 72et al. 2006; Levasseur et al. 2008; Meier 2008; Meier et al. 2008). 73

In this paper, a method for modelling the hydromechanical 74 behaviour of large landslides is presented and applied to a source 75 area of the Corvara earthflow in the Dolomites, Italy. This case 76 study is relevant, as an acceleration of the landslide could determine the involvement of a part of the village, the damming of the 78 side flank streams and the disruption of the national road running 79 on the accumulation area. 80

The method consists of two parts: forward calculations and 81 inverse analysis. In order to perform forward calculations using 82 a continuum mechanical approach with the finite element method, 83 different model components have to be implemented. The geolog-84 ical model describes the source area, and an adequate constitutive 85 model takes into consideration weight, strength and stiffness of 86 units and layers. In particular, a creep model describes the time-87 dependent behaviour of the material forming the shear zones. 88 Additionally, a hydrogeological model describing the transient 89 distribution of pore water pressures is used to approximate the 90 hydraulic boundary conditions. In order to derive the parameters 91which yield a good simulation of reality, the finite element (FE) 92 model is calibrated against displacement rates measured in the 93 field, by iteratively varying the material parameters of the shear 94zones. For this task, the inverse parameter identification technique 95of Schanz et al. (2006), Schanz and Meier (2008) and Meier et al. 96 (2008) is applied. The technique is based on statistical analyses 97 and appropriate optimisation algorithms, which have been 98 adapted and tested especially for geotechnical applications. Based 99on the Corvara case study, the requirements, difficulties and prob-100lems as well as the advantages and benefits of the proposed 101 numerical modelling concept are highlighted. 102

#### The Corvara landslide

#### Setting of the landslide area

Located in a renowned tourist area in the Dolomites of Italy, the105Corvara landslide (Fig. 1) was selected for this study on the basis of106its socio-economic relevance and for the availability of an exten-107sive dataset of field investigation and monitoring data.108

The landslide area extends from Corvara in Badiato Pralongià, 109 from about 1,600 to 2,100 m a.s.l. The landslide can be described as 110 an active slow-moving earthflow with an estimated volume of 30 111 million m<sup>3</sup>. It damages a national road and a set of facilities 112

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Fig. 1 Location and overview of the Corvara earthflow

113 including ski infrastructures, electricity lines and a golf course. In the worst-case scenario, the landslide might accelerate and affect 114115some buildings located at its toe and possibly endanger downstream settlements by damming the torrents running at its flanks. 116117For this reason, geological, geomorphologic and geotechnical anal-118 yses of the landslide have been carried out since 1996 with the 119support of the autonomous province of Bolzano-South Tyrol, 120together with the Corvara municipality (Corsini et al. 2001; Soldati 121et al. 2004; Corsini et al. 2005; Panizza et al. 2006; Borgatti et al. 1222007b; Borgatti and Soldati 2010).

zano—South Tyrol, about 30° of inclination, a i et al. 2001; Soldati tectonic joint sets genera 2006; Borgatti et al. (Corsini 2000). The overall slope is primarily controlled

Bedrock of the landslide site is mostly composed of Tri-123 assic flysch-type rock masses, La Valle and San Cassiano 124units, which consist of an alternation of volcano-clastic 125sandstones, marly limestones and clay shales. The ratio of 126hard to soft rocks varies from 1 to more than 2 (Corsini et 127al. 2005). Bedrock forms a monocline dipping upslope at 128about 30° of inclination, and shows three to four major 129tectonic joint sets generated during the Alpine orogen 130 (Corsini 2000). The overall geomorphologic setting of the 131 slope is primarily controlled by the attitude of bedding and 132



Fig. 2 Displacement vectors (a) and displacements (b) measured in source area S3 between 2001 and 2004 (GPS data from Panizza et al. 2006). Benchmark 49 was measured starting from 2003; vector has been scaled up respectively. Location of boreholes and of cross section of Fig. 5 is also reported (a)

joints and, secondarily, by the action of Pleistocene glaciers
and of Holocene weathering and mass wasting processes
(Corsini et al. 1999; Corsini 2000).

At present, in the Corvara landslide, distinct source (S), track 136 (T) and accumulation (A) areas can be outlined. The source area 137 itself can be subdivided into four sectors (S1, S2, S3 and S4 in 138

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Fig. 1). Observations made on borehole cores, radiocarbon data
and historical archives point to a long-term landslide evolution
characterised by periods of increased activity during which the
main scarp probably retrogressed, the accumulation zone grew
and the earthflow foot advanced down the valley (Corsini et al.
2005; Panizza et al. 2006).

145 In the period 2001–2004, movements in the source area were 146 "very slow" to "slow" (following Cruden and Varnes 1996), ranging 147 from 50 to 1,000 mm/year, with acceleration phases taking place 148 mainly in autumn and late spring, after prolonged rainfall and/or 149 snowmelt events. Hence, surges can be expected in the scenarios of 150extreme meteorological events and/or of excess pore pressure 151build-up due to activation of local shallow earthflows. This would 152imply a large amount of material to reach the track zone, with 153eventual total reactivation of the Corvara landslide and subsequent large damage. For this reasons, displacement rates in source 154155area S3 have been monitored by RTK D-GPS during 15 monitoring 156campaigns carried out four to five times a year in the period from 2001 to 2004. Two master stations were set in stable areas outside 157158the landslide. The displacement history of benchmarks 23-30 is 159plotted in Fig. 2, showing the norms of 3D displacement vectors for 160each measurement date and their directions. The gap periods of 161 10 months in the records are partly due to the existence of a thick 162snow cover in winter and spring seasons, during which measure-163 ments were not possible but significant displacements occurred. 164 The data exhibit approximately linear trends. Rates of around 1650.1 m/year were measured at benchmarks 24, 26 and 27, lying on the main landslide body of source area S3. Significantly higher 166 displacement rates of around 0.2 m/year were observed in areas 167 168 where, in addition to the movement of the main landslide body, the slope is also affected by shallow landslides (GPS benchmarks 16917023, 25 and 28). The GPS benchmarks 29 and 30, located in a 171relatively stable area below the crest of the slope and above the 172active part of source area S3, did not show significant displace-173ments (Fig. 2).

#### 174 Geological model of source area S3

A geological and geotechnical model of the whole Corvara landslide was made available by Panizza et al. (2006), including surface
topography, stratigraphic profile, depth of sliding zones and dimensions of landslide bodies characterised by different displacement rates.

Surface topography was obtained by profiling a DEM produced 180181 in 2005 by the autonomous province of Bolzano using airborne 182LiDAR. Its nominal elevation accuracy is in the order of 1 m. A large number of geotechnical laboratory tests were carried out on 183184samples of the landslide body in order to characterise the mate-185rials (grain size distribution, Atterberg limits, etc. on 25 soil sam-186ples, see Panizza et al. 2006) and assess shear strength (direct shear 187 tests on 5 samples, see Panizza et al. 2006). Stiffness under differ-188 ent stress loads, consolidation behaviour and oedometric creep 189 behaviour was analysed with oedometer tests, also with prolonged 190 creep phases, isotropic compression and deviatoric creep tests 191(Schädler 2008). The landslide body is made up of a normally 192consolidated soil matrix of silty clays and clayey silts, which 193encloses coarser components, such as a variety of angular gravel-194 size particles, up to rock blocks. These consist of volcanoclastic 195and calcareous sandstones, marly limestones or dolostones. The 196mechanical behaviour of the shear zones is assumed to be mainly controlled by the properties of the clay-rich soil matrix (Table 1).

Underground boundaries, including the depth of sliding sur-199faces, have been obtained by interpreting field evidence, borehole 200 stratigraphy, geoelectric and seismic refraction data, and inclinom-201eter measurements. In source area S3, according to inclinometer 202C4 (Fig. 2), the landslide body is prevalently moving along a basal 203shear zone 40 m deep (Fig. 3). From inclinometer and TDR cables 204measurements, it can be inferred that the thickness of the main 205shear zones is in the order of 1 to 2 m (Corsini et al. 2005). In the 206 lower part of source area S3, field evidence suggests that the 207 landslide body thins out to a few metres due to the presence of a 208buried bedrock ridge. In the geological model, the basal surface of 209rupture of source area S3 is slightly dipping upslope in the foot 210 area and outcropping upslope the track zone. In some sectors, a 211hummocky morphology and the presence of lateral ridges indicate 212that shallow earthflows are locally active over secondary shear 213214zones, 3 to 10 m deep.

Below the main shear zone, old landslide material, colluvium 215and bedrock were found in borehole core of inclinometer C4. 216Since these materials gave very similar responses during the geo-217physical soundings (Panizza et al. 2006) and inclinometer C4 218showed no movements below 40-m depth, when assigning prop-219erties to the different parts of the geological model, these materials 220 were treated as one single unit (Fig. 3). Concerning 221hydrogeological conditions, two open pipe piezometers (in bore-222 holes Cpz2 and C7) and one unsealed and uncemented inclinom-223 eter case operating as open pipe piezometer (C4) lie in source area 224225S3 (Fig. 2, Table 2).

Measurement series recorded by electric transducers equipped 226 with data loggers (acquisition time set to 30 min) indicated a ground-227water depth varying from 0 to 8 m in the period 2001-2004 and 228 revealed the existence of two different types of overlapping ground-229water regimes. The first is connected to streams, ponds and marshes 230and therefore shows relatively small variations (C4 in Fig. 4); the 231second is linked to the infiltration of rainfall and consequently 232undergoes much larger seasonal fluctuations (Cpz2 in Fig. 4). In 233 order to model the hydrogeological conditions for the entire 2D 234slope model, a single continuous aquifer marked by one average 235groundwater depth of 1 m was initially idealised. The geological and 236hydrogeological model of the slope is shown in Fig. 5. 237

#### Inverse parameter identification technique

Instead of varying the model parameters in a conventional, man-239ual trial-and-error procedure, an inverse parameter identification 240 approach using the back analysis method (Cividini et al. 1981) was 241applied to calibrate the numerical model of the slope and to back-242 calculate a subset of material parameters for which the available 243field measurements indicate a high sensitivity. The identification 244approach consists of a procedure performed in several substeps 245during which parameters are iteratively changed to achieve better 246fit between the model results and the field measurements. Good-247ness of fit is measured by the objective function f(x), which has to 248be defined individually for each specific back-calculation task. The 249objective function used here is the mean-square deviation between 250monitoring data and simulation results. In order to confine the 251best fit searching procedure to reasonable solutions in physical 252and engineering terms, a bounded parameter search space  $\Omega$  is 253defined. 254

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<b>Q3</b> .1	Table 1	Average	geotechnical	parameters	of	the	landslide	material	from	source
	area									

+1.0		Value
61.2		Value
t1.3	Unit weight y	15–22 kN/m <sup>3</sup>
t1.4	Sand fraction	15 %
t1.5	Silt fraction	50 %
t1.6	Clay fraction	35 %
t1.7	Lime content	39.7-55.5 %
t1.8	Plasticity index	10-30 %
t1.9	Natural water content	20-45 %
t1.10	Plasticity Chart	MH-OH, ML-OL
t1.11	Undrained cohesion c <sub>u</sub>	30–100 kN/m <sup>2</sup>
t1.12	Effective peak friction angle $\phi$	20–30°
t1.13	Effective peak cohesion c'	10–35 kN/m <sup>2</sup>
t1.14	Residual friction angle <mark>(</mark> ,	15–20°
t1.15	Modified compression index $\lambda^*$	0.050-0.064
t1.16	Modified swelling index K*	0.020-0.035
t1.17	Modified creep index <mark>µ</mark> *	8.09×10 <sup>-4</sup> -1.46×10 <sup>-3</sup>
t1.18	Permeability k	2.10×10 <sup>-10</sup> m/s
t1.19	Oedometer modulus E	5–53 MN/m <sup>2</sup>
t1.20	Shear modulus G	5,560 kN/m <sup>2</sup>
	Poisson's ratio v	0.35

From Corsini et al. (2005), Panizza et al. (2006), and Schädler (2008)

In this work, the solution of the optimisation problem (i.e.,
 minimisation of the objective function) is based on a strategy
 called Shuffled Complex Evolutionary algorithm (SCE)

proposed by Duan et al. (1992, 1993, 1994). The SCE belongs 258to a group of algorithms that combine methods and strategies 259of different optimisation algorithms in order to overcome 260weak points, restrictions and disadvantages of the individual 261methods when used alone. Prior to the application of an 262optimisation scheme to a back-calculation problem, it is high-263ly recommended to gain more information on the initially 264unknown objective function topology. For this purpose, a 265number of forward calculations are performed using randomly 266chosen parameter sets within physically reasonable ranges, 267and the objective function value is calculated for each param-268eter set. To visualise this kind of multi-dimensional data, a 269scatter-plot matrix as shown in Fig. 6a is often used. In this 270type of scatter-plot matrix, each row and column correspond 271to one parameter being varied, where each subplot can be 272interpreted as projection of the multi-dimensional objective 273function topology (Manly 1944). To avoid appending an addi-274tional row to the matrix showing the objective function value 275on its vertical axis, these plots are moved to the diagonal 276elements of the plot matrix. For each forward calculation of 277the randomly chosen parameter sets, one data point can be 278plotted in each of the subplots of a scatter-plot matrix. To 279allow for an assessment of the distribution of a certain ob-280jective function value range, a filtered subset of the randomly 281chosen parameter sets is usually plotted. If only the best 282items are plotted, the resulting point clouds give an impres-283 sion of the optimal objective function value range. 284

For example, a simple analytical function is used for generating 285the scatter-plot matrix of Fig. 6, where only parameter sets are 286shown leading to  $f(x) \le 0.5$  (10,000 parameter sets had been calcu-287lated within  $-1 \le x_{1,2,3} \le +1$  of which 281 sets satisfy  $f(x) \le 0.5$ ). The 288three columns and rows of Fig. 6a correspond to the parameters  $x_1$ , 289 $x_2$  and  $x_3$  of the objective function. As visible from Fig. 6b, the 290optimal value range envelopes show a "correlation" between  $x_1$ 291and  $x_{3}$ . Additionally, from the analytical function, it is to be 292



Fig. 3 Internal stratification of the geological model (inclinometer data from Corsini et al. 2005 and Panizza et al. 2006). Solid red line indicates inclinometric profile and layering observed along the entire length of the tube; dotted red line indicates inclinometric profile after the rupture of the tube at 40-m depth

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2.1	Table 2 Gro	oundwater monitoring devices		
2.2	Label	Diameter (inch)	Depth (m)	Туре
2.3	C4	2	60	Unsealed/uncemented inclinometer case operating as open pipe piezometer
2.4	Cpz2	2	45	Open pipe piezometer fissured only at 39–45-m depth
	C7	4	88	Open pipe piezometer

expected that  $x_1$  is the least and  $x_3$  is the most sensitive parameter for f(x). The following statements hold:

- 295- The projected shapes of the isosurfaces for f(x) = 0.5 of Fig. 6b296correspond very well to the envelopes of the point clouds of the297individual subplots of Fig. 6a.
- 298 The correlation of  $x_1$  and  $x_3$  is nicely visible in the correspond-299 ing subplots and for the point cloud shown; a 2D linear corre-300 lation coefficient of -0.74 is calculated. As to be expected, for 301 the other parameter combinations, no correlation is visible.
- 302 The diagonal elements of the scatter-plot matrix provide in-303 sight to the local sensitivity of the objective function range 304shown for  $x_1$ ,  $x_2$  and  $x_3$ . First, only one lower tip of the point 305 cloud envelope is visible, what indicates that only one opti-306 mum is existing within the investigated range. Second, as more sensitive a parameter is, as more "pointy" the lower tip of the 307308 point cloud envelope should be. As expected,  $x_1$  is the least and 309 $x_3$  is the most sensitive parameter. In general, if an inverse 310 problem is well posed, each of the diagonal plots should

present one firm extreme value. Otherwise, the respective parameter may not be identified reliably. 312

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- The diagonal elements of the scatter-plot matrix indicate 313 that the global optimum is somewhere near  $x_1=0$ ,  $x_2=0$  314 and  $x_3=0$ . 315

This kind of statistical analysis of the results of forward calculations can be used to determine those parameters which are317lations can be used to determine those parameters which are318indifferent to the system response or dependent on each other.319These parameters can be removed prior to back-calculation. Fur-320thermore, the remaining parameters can be classified according to321their influence (Schwarz 2001).322

#### **Forward calculations**

#### Hydrogeological model

Steady state and transient groundwater flow calculations were 325 carried out applying the FE code SEEP/W (Krahn 2004). Zero flow 326



Fig. 4 Piezometric data and rainfall during 2001-2004 monitoring period



Fig. 5 a 2D geological model of source area S3. See Fig. 2 for location. Point 24B is based on inclinometric measurements. b Simplified hydrogeological model assuming an average water table to be implemented in the seepage model (piezometer data from Panizza et al. 2006)

327 was allowed through the basal boundary of the geological model, 328 and fixed groundwater heads were prescribed at its lateral bound-329 aries based on monitoring data. Water levels were then generated 330 by means of a 2D slope infiltration and seepage model. Input flow 331 rate was calculated monthly according to the Thornthwaite (1948) 332 formula, using rainfall, snowmelt and temperature data recorded 333 at the on-site meteorological station (observation period 2001-3342004, Table 3).

335 The calculated effective recharge was simulated using a tran-336 sient flux boundary condition applied at each node on the slope 337 surface profile (q in m/s, see Krahn 2004). At every node, the 338 potential seepage review boundary condition was adopted in 339 order to avoid ponding. A null-flux condition was imposed at 340 the base of the model and at the upslope model boundary 341 because the crest of the slope was assumed to represent the 342 main water divide. The model parameters (saturated and unsat-343 urated hydraulic conductivities, volumetric water content func-344tions and conductivity functions, here represented by a straight 345line) were estimated from grain-size distributions, Atterberg 346 limits, water content at saturation and coefficient of volume 347 compressibility of the landslide materials. Recommendations 348 within Krahn (2004) and data proposed by other authors (e.g.

Caris and van Asch 1991; Bonomi and Cavallin 1999; Malet et al. 349 2005; Tacher et al. 2005; Francois et al. 2007) were also considered. In order to further simplify the hydrogeological model, 351 isotropic hydraulic permeability was assumed for all materials, 352 except for shallow landslide bodies in which the vertical permeability was assumed to be three times higher than the horizontal one (Table 4). 355

The infiltration and seepage model was calibrated by a trial-356 and-error procedure against the monitoring data of piezometer 357Cpz2, in which groundwater level is largely controlled by infiltra-358tion (Fig. 4). Calibration was continued until an acceptable fit 359 between calculated and measured level was obtained for the re-360 charge as well as for the discharge curve (Fig. 7). Conservative 361 hydrostatic pore pressure distributions were then used in the 362 deformation model. 363

#### Finite element hydraulic-mechanical model

The kinematics of the slope during the observation period (2001– 2004) were simulated using the FE method. All calculations were carried out using the Plaxis<del>code</del> version 8.2 (2003), taking into account the effect of large deformations by means of an updated Lagrangian formulation (updated mesh analysis). Calculations 369



Fig. 6 Scheme of the scatter-plot matrix. a Multi-dimensional data plotted in a scatter-plot matrix. b Example of the objective function calculation for a simple analytical function

were performed as consolidation analyses, i.e. modelling the
stress-strain field and taking into account the time-dependent
development of pore pressures. A plane-strain geometrical configuration with the real dimensions of the slope was used. The model
was discretised using 2790 triangular 15-node elements. Horizontal

deformation fixities were assigned to the lateral boundaries and 375 total deformation fixities to the basal boundary. 376

Based on lab tests (Table 1) and on the results of calibration of377the constitutive model (Schädler 2008), the soil along the shear378zones can be regarded as a plastic material, which is characterised379

t3.1 Table 3 Average climatic data for the observation period. The calculated effective recharge was used as input in the infiltration and seepage model

Month	Mean monthly air temperature (°C)	Mean monthly rainfall (mm)	Mean monthly snowmelt (mm)	Mean monthly evapotranspiration (mm)	Mean monthly effective recharge (mm)	t3.2
Jan	-4.7	29.0	0.0	0.8	28.1	t3.3
Feb	-3.1	29.1	10.3	1.1	38.4	t3.4
Mar	0.5	46.8	22.9	7.4	62.3	t3.5
Apr	2.7	54.1	6.1	30.1	30.1	t3.6
May	8.3	92.5	0.0	92.5	0.0	t3.7
June	12.4	82.4	0.0	82.4	0.0	t3.8
July	13.4	97.9	0.0	97.9	0.0	t3.9
Aug	14.1	75.9	0.0	75.9	0.0	t3.10
Sept	9.0	80.5	0.0	80.5	0.0	t3.11
Oct	5.4	69.8	0.0	50.6	19.1	t3.12
Nov	0.8	149.6	11.0	4.9	155.8	t3.13
Dec	-2.5	39.1	20.3	1.1	58.3	t3.14
Total		846.6	70.7	524.5	392.2	

### Landslides

t4.1 Table 4 Saturated hydraulic conductivity values used in the trial-and-error procedure for the calibration of the steady-state groundwater flow calculation

		•	, ,		
Layer		Fixed values and constraints (m/day)	Calibrated values (m/day)	Adopted values (m/s)	t4.2
D	Active shallow landslide bodies	D2>D1; <0.09	0.03	3.47E-07	t4.3
		D1≥C	0.01	1.16E-07	t4.4
C	Main landslide body	0.009		1.04E-07	t4.5
В	Old landslide body	A <b<c< th=""><th>0.004</th><th>4.63E-08</th><th>t4.6</th></b<c<>	0.004	4.63E-08	t4.6
A	Bedrock	0.0009		1.04E-08	

 $D_1$  horizontal,  $D_2$  vertical

380 by a pronounced time-dependent behaviour (Picarelli et al. 2000; 381 Augustesen et al. 2004). Therefore, the Soft Soil Creep model was 382 used as a constitutive model for these zones (Vermeer and Neher 383 1999). A set of three parameters (effective cohesion c, effective 384 friction angle  $\varphi$  and dilatancy angle  $\psi$ ) is required to model failure according to the Mohr-Coulomb criterion. Two further parameters 385386 are used to model the amount of plastic and elastic strains and their 387 stress dependency. The modified compression index  $(\lambda^*)$  represents the slope of the normal consolidation line. The modified swelling 388 389index  $(\kappa^*)$  is related to the unloading or swelling line. The modified creep index  $(\mu^*)$  measures the development of volumetric creep 390 391deformations with the logarithm of time.

392 Due to the age of the landslide activity in source area S3 and the 393 continuous nature of the sliding processes, it was assumed that in 394 the long term, the shear zones have undergone relative displace-395ments in the range of at least tens of metres. Therefore, the 396 material of the shear zones is assumed to have reached the residual 397 strength. As the subsoil away from the shear zones shows little 398 internal deformations (Fig. 3), the material behaviour was 399modelled as linear-elastic to account for the gravitational loads that these materials exert onto the shear-zone lavers. 400

401The initial stress state at the beginning of the modelled time402span, i.e. in the year 2001, is mainly a consequence of the long-403term history of the slope. Therefore, the initial stress state in the404model was generated by simulating a simplified loading history,



Fig. 7 Observed and calculated groundwater depths in borehole Cpz2 from December 2001 to March 2003 during recharge and discharge phases

based on the knowledge about the slope evolution. Modelling of 405the different phases was performed in six phases: gravity loading, 406 unloading by weathering and erosion, loading by glaciers, forma-407 tion of weak zones, unloading after glaciation and creeping. It was 408 assumed that already prior to the last glaciation, the slope was 409 characterised by a gently inclined profile. Therefore, in a first 410calculation phase, a stress field was created by gravity loading 411 based on the actual topography and assuming a homogeneous 412 linear elastic material, whose specific weight equals that attributed 413 to the actual bedrock. During gravity loading, Poisson's ratio was 414 adjusted to result in a ratio between horizontal and vertical stress-415es corresponding approximately to a  $K_0$  value of 0.8. Then, the 416 value of Poisson's ratio was changed to the assumed current value 417 (0.33), which was then used in further calculation phases. In a 418 second calculation phase, the slope model was unloaded by low-419ering the specific weight of all layers, except for the bedrock, to 420 present-day values. In a third phase, a distributed load of 421 1,000 kN/m<sup>2</sup> was applied perpendicularly to the ground surface 422 to simulate loading by Pleistocene glaciers. In a fourth phase, 423 weak layers were inserted into the model as a result of deep 424weathering during the glaciation and deglaciation phases. In a 425fifth phase, the slope was unloaded very fast to its actual state 426 immediately after the shear-zone layers had been inserted. In 427a sixth phase, the shear-zone materials were left creeping 428 under the assumed average water pressures until approximate-429ly constant displacement rates were observed with respect to 430the time-scale of the simulated monitoring period. The dura-431tion of this phase (10,000 days, approx. 27 years) had to be 432 defined arbitrarily to comply with this criterion. The stress 433 state reached at the end of this last phase of the loading 434history was taken as initial stress state for the simulation of 435deformations in the monitoring period. 436

A first-trial forward calculation, using parameter values directly 437from the laboratory tests, was carried out (Table 5). The calculated 438total displacements at the end of the 3 years of the monitoring 439period appeared to be underestimated by the model, with total 440 displacements in the order of 7 cm with respect to 30-70 cm 441 measured in the field. Anyhow, in the most active region, the shape 442 of the displacement profile and the direction of displacement 443 vectors were in qualitative agreement with the measurements. 444

#### Inverse analysis

#### Statistical analysis

The results of the first-trial calculation suggest that the material 447 parameters are not the same for all shear zones (i.e. basal shear 448 zone C and shear zones of shallow active landslides D1, D2 and D3, 449

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t5.1 **Table 5** Experimental parameter values used for all the shear zones in the firsttrial forward calculation. Shear strength parameters from Panizza et al. (2006) and stiffness parameters and creep parameters by oedometer tests in Schädler (2008), as shown in Table 2

t5.2	Material parameter	Value
t5.3	$\lambda^*$	0.057
t5.4	<i>к</i> *	0.028
t5.5	$\mu^*$	1.2×10 <sup>-3</sup>
t5.6	$\Phi$	20°
t5.7	С	27 kN/m <sup>2</sup>
	$\psi$	0°

see Fig. 5). Hence, in the statistical analysis of the model behaviour,450some of the parameters were correlated, while others were chosen451to be identified independently, trying to minimise the number of452variable parameters, but not to oversimplify the model.453

The displacement rates depend on shear strength and creep 454behaviour of the shear zones, which is in turn controlled mainly by 455 the modified creep index  $\mu^*$  and is also related to their stress-456dependent compressibility and vice versa. The latter is described 457by the modified compression index  $\lambda^*$ . This means that  $\lambda^*$  and  $\mu^*$ 458 depend on each other or the ratio of them is about constant (Mesri 459and Godlewski 1977; Mesri and Castro 1987). Both parameters are 460 unknown along the shear zones of landslide source area S<sub>3</sub>. They 461 were identified by varying them within large search intervals 462

t6.1

material	paramete r	unit	fixed value		var	y between		constraint
					max	ln	ln	
				min.		(min.)	(max.)	
C basal shear-zone	λ* (C)	none		0.04	1	-3.22	0	
	к* (С)	none	0.02					
				0.00				
	μ* (C)	none		1	0.5	-6.91	-0.69	$\mu^{*}(C) < 0.5 \lambda^{*}(C)$
	φ(C)	0		15	25			
		kN/m						
	c (C)	2	0.3					
		_						
D1 secondary shear-zone	λ* (D1)	none				λ* (D1) =	λ* (C)	
of front block	κ* (D1)	none	0.02					
	μ* (D1)	none			μ	$\iota^*(D1) = \mu$	ι* (D2)	
	φ (D1)	0		15	25			
		kN/m						
	c (D1)	2	0.3					
D2 secondary shear-zones	λ* (D2)	none		0.04	1	-3.22	0	$\lambda^{*}(D2) > \lambda^{*}(C)$
of active shallow	κ* (D2)	none	0.02					
landslides				0.00				$\mu^* (D2) < 0.5 \ \mu^*$
	μ* (D2)	none		1	0.5	-6.91	-0.69	(C)
	φ (D2)	0		15	25			
		kN/m						
	c (D2)	2	0.3					
D3 secondary shear-zone	λ* (D3)	none			λ	.*(D3) = 7	.* (D2)	
(uppermost part)	κ* (D3)	none	0.02					
	μ* (D3)	none			μ	ι* (D3) = μ	ı* (D2)	
	φ (D3)	0				$\varphi$ (D3) = $\alpha$	p (D2)	
		kN/m						
	c (D3)	2		5	50			

In spite of linking a number of parameters, still, eight parameters remain to be identified, namely  $\lambda^*$  (C),  $\mu^*$  (C),  $\phi$  (D1),  $\lambda^*$  (D2),  $\mu^*$  (D2),  $\phi$  (D2) and c (D3). A statistical analysis, based on 7,670 calls of the forward calculation, was carried out on these eight parameters, varying them within the intervals specified in Table 6. The corresponding scatter-plot matrix is presented in Fig. 8

463 (Table 6). As a result of the long-term displacements (up to 75 cm 464 in 2001-2004 monitoring period), residual strength conditions 465 were assumed. Accordingly, an arbitrary value of 0.3 kN/m<sup>2</sup> has 466 been used for residual cohesion in order to avoid numerical 467 instability in the calculations. Due to the situation that in shearzone domain D<sub>3</sub>, the activity rate is lower (cumulative displace-468 469ments from 5 to 30 cm in 2001-2004 monitoring period) and it was 470assumed that the corresponding shear surface is not fully devel-471oped and strength is not fully softened. Therefore, a search inter-472 val for cohesion also was adopted here (Table 6). Representative 473 values of the friction angle  $\phi$  are assumed to be controlled also by 474 the presence of coarser components, such as rock blocks. Conse-475quently, the friction angles of the shear zones were selected to be 476 identified, varying them between 15° and 25°, i.e. the estimated

477 residual friction angle of the soil matrix and the friction angle of bedrock in heavily weathered condition (Panizza et al. 2006). The 478 modified swelling index of  $\kappa^*$  was fixed based on laboratory data: 479Values obtained in five oedometer tests on different samples from 480 the soil matrix of the landslide material (fraction <2 mm) ranged 481 between 0.01 and 0.05, with an average value of 0.026. Due to the 482 influence of less deformable coarser components, representative 483 values of  $\kappa^*$  for the shear zones were assumed to be lower, i.e. 484stiffness is higher than that of the fine-grained fraction. Therefore, 485the value of 0.02 was used. To avoid physically and numerically 486 unfavourable parameter combinations and to minimise the num-487 ber of unsuccessful attempts, two parameter constraints were 488 prescribed in all parameter sets, based on literature and lab data: 489The highest  $\mu^*$  value be smaller than half of the lowest  $\lambda^*$  value. A 490



Fig. 8 Scatter-plot matrix for the slope model. Basal shear zone C and Secondary shear zones D1, D2 and D3 (see Fig. 5 and Table 6). The numbers are 2D linear correlation coefficients as described in Section 3 and Fig. 6. In case the coefficient falls below 0.6, the numbers are in *brackets*. In case the coefficient is below 0.3 no number is shown

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measured] in the two steps of the calibration procedure (1: first step optimisation; 2: second step optimisation)

Relative errors between simulated horizontal displacements and GPS measurements at points 23–28 [(measured – calculated)

**Table 7** 

491 summary of all above-described parameter links and parameter492 constraints is given in Table 6.

To indicate the expected shape and location of the optimal 493value range, this matrix shows only the parameter combina-494 tions related to the 83 lowest objective function values (marked 495by blue points in the matrix). None of the plots of the scatter-496 plot matrix have a clear-cut shape; therefore, the problem must 497 be considered as underdetermined and it is advisable not to 498499increase the number of varying parameters. However, the ob-500jective function plots give some pieces of information as to the most probable ranges of the best parameter values. For the 501friction angle  $\varphi$  of the basal shear zone C, the best parameter 502sets are all located in the lower part of the search interval, i.e. 503between 15° and 19°, whereas for  $\mu^*$  of this zone, they accu-504 505mulate in the upper part of the interval. Less clearly, this can 506be noticed also for the values of  $\lambda^*$ , because  $\mu^*$  and  $\lambda^*$  appear 507 to be correlated (linear correlation coefficient of 0.78), as previously expected. None of the 83 best parameter combina-508tions have a value of  $\mu^*$  in the uppermost part of the search 509510interval, i.e. between logarithmised  $\mu^*$  values of -0.9 and -0.69. The information obtained for the parameters of the 511secondary shear zones D1, D2 and D3 is less clear. As in none 512of the displayed best parameter sets  $\varphi$  of the front slide (D1) is 513514below 17° and furthermore in 15 of the 18 best sets,  $\varphi$  values are between 18° and 23°, and the statistical analysis indicates 515that an optimum value of this parameter can be identified in 516the medium range of the search interval. Relatively good 517objective function values can be obtained independent of the 518cohesion value assigned to shear-zone domain D3, except for 519520values from the lowermost part of the interval. In contrast, relatively good fits are observed for a wide range of friction 521522angles of D<sub>3</sub> but not for values from the uppermost part of the search interval. In the case of  $\lambda^*$  for shallow landslides, the 523accumulation of plotted points on the right side of the interval 524as well as the weak correlation between  $\lambda^*(C)$  and  $\lambda^*(D_2, D_3)$ 525526are direct consequences of the parameter constraint demand-527ing for  $\lambda^*(D_2, D_3) > \lambda^*(C)$ . The objective function projection for the parameter  $\mu^*$  of these layers shows good model fits 528529independent of the parameter value, except for the uppermost 530 part of the search interval (between logarithmised  $\mu^*$  values of -1.3 and -0.69) where none of the 83 best parameter sets are 531532plotted. From the scatter-plot matrix in Fig. 8, it is not clear whether the search interval for  $\lambda^*$  of the shear zones of the 533shallow landslides (D2 and D3) is sufficient since the data 534points with low deviation values accumulate near the upper 535boundary. As for higher values of  $\lambda^*$  (e.g. between 1 and 2, 536logarithmised values between o and 0.69), the percentage of 537538failed forward calculations increased considerably and it was 539decided not to enlarge the interval.

#### 540 $\qquad$ Identification of shear-zone parameters with the SCE algorithm

After the statistical analysis, the search intervals presented in Table 6 541were used also for the optimisation procedure applying the SCE 542algorithm, as described in the "Inverse parameter identification 543544technique" section. After 1,100 calls of the forward calculation, the 545SCE algorithm was not able to further reduce the objective function value. The lowest value reached  $9.2 \times 10^{-4}$ . The parameter sets iden-546 547tified by the algorithm using the complete reference dataset are 548shown in Table 7.

PS point	Step	GPS Survey											t7.5
		Sep 01	Jun 02	Aug 02	Sep 02	0ct 02	Jun 03	Aug 03	Sep 03	Jun 04	Aug 04	Oct 04	t7.5
m		0	-0.11	-0.12	-0.13	-0.15	-0.01	-0.01	-0.02	0.11	0.15	0.11	t7.4
	2	0	-0.18	-0.18	-0.19	-0.20	-0.11	-0.11	-0.11	0.02	0.07	0.01	t7.5
4		0	-0.72	-0.28	-0.32	-0.31	-0.07	-0.21	-0.18	0.02	0.04	0.03	t7.(
	2	0	-0.78	-0.37	-0.40	-0.39	-0.10	-0.27	-0.24	-0.01	0.00	00.0	t7.7
2		0	-0.38	-0.34	-0.35	-0.45	-0.04	-0.09	-0.08	0.07	0.05	0.04	t7.8
	2	0	-0.52	-0.45	-0.45	-0.57	-0.13	-0.18	-0.17	0.00	-0.03	-0.04	t7.9
6		0	-0.50	-0.43	-0.27	-0.30	-0.05	-0.17	-0.09	0.10	0.08	0.10	t7.]
	2	0	-0.56	-0.54	-0.36	-0.40	-0.09	-0.24	-0.16	0.06	0.03	0.06	t7.]
2		0	-2.54	-0.80	-0.79	-0.88	-0.27	-0.30	-0.39	-0.13	-0.14	-0.10	t7.]
	2	0	-2.97	-0.98	-0.95	-1.04	-0.40	-0.41	-0.50	-0.22	-0.23	-0.20	t7.]
8		0	-1.11	-0.74	-0.84	-0.82	-0.04	-0.03	-0.06	0.11	0.22	0.21	t7.]
	2	0	-1.44	-0.97	-1.08	-1.06	-0.19	-0.17	-0.20	-0.02	0.10	0.09	
ne second sten o	ntimisation a n	narrowed dataset we	as used (GPS benc	hmarks 23 25 and	28)								

549 In Fig. 9, the results of a calculation using the best parameter 550set of the first step of the optimisation procedure can be compared 551to the measured horizontal displacements of GPS points 23 to 28. 552Considering the simplifications made in the model, it can be stated 553that displacements are reproduced quite well for most points, but 554underestimation occurs at GPS points 23 and 28. As these points lie above secondary shear zones, in a second step of the optimisation 555556procedure, the parameters of the basal shear zone were fixed 557at the identified best values. In this phase, a narrowed dataset was used, containing only horizontal displacements of the 558559three measurement points located above secondary shear

560 zones (points 23, 25 and 28). A total of six parameters were varied in the second step of the optimisation procedure. For 561the search, the configuration of parameter links, parameter 562constraints and search intervals was in fact modified in some 563details: The optimisation algorithm was allowed to vary the 564friction angle of D<sub>3</sub> shear-zone domain independently of that 565of D2. When fixing the parameters of the basal shear zone, 566the parameter constraint demanding for  $\lambda^*(C) < \lambda^*(D_2, D_3)$ 567was removed because it was preferred not to restrict the 568search based on a value of an identified parameter set. After 5692,092 calls, the optimisation was stopped because no 570



----- Simulation with parameters from first optimisation with SCE

--- Simulation with parameters of best fit

Fig. 9 Time series of calculated displacements and measured data for GPS points 23-28 (displacements in dm)

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t8.1 Table 8 Summary of parameter values identified with SCE algorithm for the slope model

Parameter (unit)	$\lambda^*$		μ*		Φ (°)				$c (kN/m^2)$
Zones	C, D1	D2, D3	С	D1, D2, D3	С	D1	D2	D3	D3
Complete dataset	0.62	0.96	0.17	0.31	18.1	21.6	16.2	16.2	48.3
Narrowed dataset	Fixed	0.63	Fixed	0.24	Fixed	19.5	16.4	23.8	16.9

571significant reduction of the objective function value was observed. It can be noticed that the underestimation of displace-572ments at points 23 and 28 is reduced after the second step 573574optimisation. The relative errors between simulated and mea-575sured values are shown in Table 7, with maximum relative 576errors in the order of 20 % at the end of the simulated monitoring period. The identified best parameter set is given 577 578in Table 8.

579In Fig. 9, the second-step optimisation results are compared to the 580measured time series of the horizontal displacements at GPS bench-581marks 23-28 (2001-2004 displacements are shown at the same timescale for all points). For GPS benchmarks 23, 24, 25 and 26, the whole 582583curve of the time series is nearly matching the reference data points, except for small differences, which are always below 5 cm. These 584benchmarks are located in the slope area where most of the 585586hydrogeological data have been collected; hence, the simplified 587 hydrological assumptions hold true. Conversely, the calculated 588displacement patterns are not curved enough, or too linear, at 589GPS points 25, 27 and 28. There, the displacements are smaller in summer and larger during autumn and after snowmelt infil-590591tration. Due to the simplified hydrogeological assumptions, this 592 seasonal phenomenon is not reproduced properly by the model. 593In Fig. 10, the displacement vectors calculated for the 3 years of 594the monitoring period (2001-2004) after the second step of 595optimisation are compared with those measured in the field 596by means of GPS. Reproduction of the horizontal displacements at the end of the monitoring period is good. Except for GPS 597 598points 26 and 28, vertical displacements are clearly 599overestimated, even if the low precision of the vertical displace-600 ment measurements has to be taken into account. However, the 601 direction of the simulated displacements is subparallel to the 602 slope, as observed in the source area of the Corvara earthflow.

Qualitatively, the modelled displacement profile at point 24 is in 603 accordance with that measured by the nearby inclinometer C4. 604

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#### Conclusions

The case study of the Corvara earthflow is promising, as a 606 large amount of relevant high-quality data, obtained at several 607 locations, mainly with continuous or semi-continuous acqui-608 sition frequency, are available. In fact, geomorphological evi-609 dence and monitoring data at the local scale were exploited in 610 support of the development, running, calibration and valida-611 tion of an FE continuum model. In particular, the model 612 calibrated via an inverse parameter identification technique 613 was able to simulate the displacement occurred at several 614 monitoring points in the source area S3 with average relative 615errors for horizontal displacements at the end of the simulat-616 ed period lower than 7 %. 617

Applying the inverse analysis makes the calibration proce-618 dure much more objective and repeatable. Beyond that, these 619 methods provide statistical information about sensitivity and 620 interdependence of model parameters. In principle, the defini-621 tion of the overall modelled problem improves with any addi-622 tional value measured in the field, and calibration quality can 623 be quantified via the objective function. Obviously, an increase 624 of the temporal resolution of the displacement measurements 625 and of the spatial resolution of the pore pressure measure-626 ments could improve the calculated displacements obtained in 627 this study. The longer and the more comprehensive the time 628 series of measurements are, the more parameters can be iden-629tified, which until now had to be fixed based on assumptions. 630 Quantitative results-objective function values, correlations, 631 etc.-obtained by the statistical analyses and during the opti-632 misation allow for judging whether a refinement of the model 633





634 improves its quality or if an apparently more realistic model
635 will lead to further uncertainty. This type of information can
636 hardly be gained when model calibration is performed by
637 means of a traditional trial-and-error procedure.

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- Q2. Please indicate the significance of the asterisk in Table 5.
- Q3. Please check Tables 1-8 if captured and presented correctly.

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