8. Analysis of deformations in Puriscal

8.1. Methodology

To do the deformation analysis of the network in Santiago de Puriscal, some prerequisites must be fulfilled. The network of all the epochs must be adjusted and information on the standard errors of all points must be known. To do an approximate analysis it is sufficient to have information on the error of each point, but for an exact analysis the covariance matrix from the adjustment must be known. The theoretical approach of deformation analysis was described in chapter 6. To do the analysis the program DEFANA, which is a part of the PANDA package (see GeoTec GmbH, 1992) was used. For the program to be able to do an exact analysis some conditions must be fulfilled

- Approximate co-ordinates must be the same in both epochs.
- The adjustment of each epoch must be a free network adjustment
- Complete covariance matrix must exist for both epochs
- The same free parameters for both networks
- Same point used as datum defining in both epochs

The configuration of the networks can be different for the two epochs. The analysis starts with an S-transformation, in order to transform the two epochs to a common datum. Then the point with the most significant displacement is sought by the help of a congruency test (see chapter 6.6. and 6.7.). The point with the most significant displacement is removed from those defining the datum. The removal is repeated until no significant movement can be found. After this process has been finished an analysis of the individual movement of each moved point is done. The results will show which points have not moved, i.e. is still datum defining, and which have moved.

8.2. Displacement in the plane

For the calculations of displacements in the plane the 2-D possibilities of the PANDA packages where used. To do the analysis, all four datum defects were used; namely translation of X and Y, the rotation of the network and the scale. This basically means that those four factors are corrected for in the calculations. If for example there is present some scale difference between epochs in the distance-observation device used, it will be taken care of. The confidence level used for the calculations is 95%. A deformation analysis was done for all possible configurations of epochs; between March 1991 and May 1991, between March 1991 and August 1992 and between May 1991 and August 1992. For all adjustments a complete covariance matrix was used, thus all the analyses are exact and not approximate. Results showing displacements and their error ellipses were plotted by PANDA and modified afterwards.

8.2.1. Displacement between March 1991 and August 1992

This analysis involves most points, a total of 24. Those two networks are the ones showing the least error ellipses and the time between the epochs is the longest. The analysis of those epochs should therefore show the most accurate results of all.

The global congruency test showed a highly significant displacement in the network. There should therefore be no doubt that deformations exist in the network.

Number of identical points	24
Degrees of freedom	71
Standard error of unit weight	0.86
F-distribution value	1.55
Test value	5.00
Number of displaced points	7

Table 8.1. Results of deformation analysis between March 1991 and August 1992.

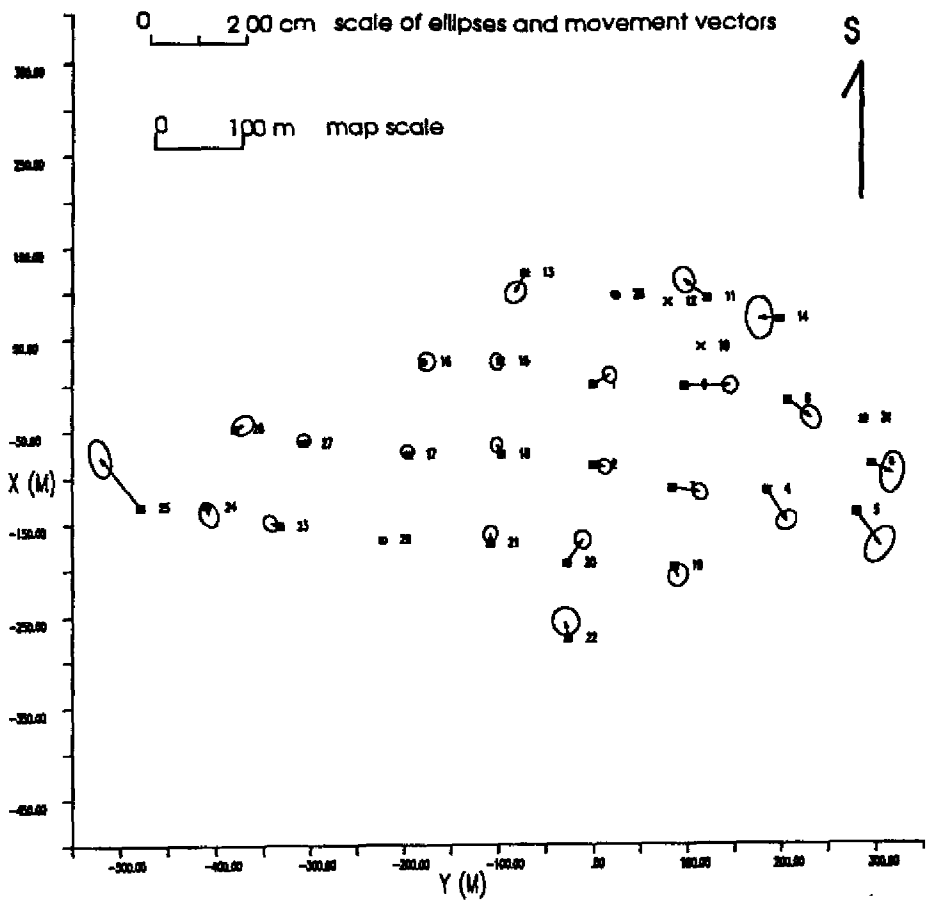

Figure 8.1. Movements in Puriscal between March 1991 and August 1992. Please note that south is upwards in this figure.

All points, the displacement vectors and the error ellipses of the displacements are shown in the figure. Of the points shown only the following points have a significant movement.

point no.	displacement (mm)	standard error of displacement (mm)
1	4.0	1.4
3	5.9	1.6
4	7.9	1.9
5	8.8	2.8
9	9.8	1.6
20	6.0	1.8
25	13.8	4.0

Table 8.2. Significant displacements between March 1991 and August 1992.

It can be seen that the detected displacements are very small, thus very accurate observations would be needed to find displacements in the other points.

Taking a look at the figure it can be seen that the point showing the biggest movement is number 25. This point lies in outskirts of the town and is actually the only point on the other side of the top of the hill. Therefore it could be believed that this point is standing still and all the rest of the network has been moving. One other thing to be noted in the figure is the movement direction of points 1, 3, 4, 5 and 9. Those all move in the same direction. In this part a steep slope goes downwards in the same direction.

8.2.2. Displacement between May 1991 and August 1992

In this analysis the chances of detecting any movements are small, the identical points only cover the centre of Santiago de Puriscal and the error ellipses of the May 1991 network are big compared to the error ellipses of the August 1992 network. The analysis shows this to be right as no displacement could be detected, i.e. the global congruency test showed the configuration of points to be identical in both networks.

Number of identical points	11
Degrees of freedom	53
Standard error of unit weight	0.92
F-distribution value	1.80
Test value	1.77
Number of displaced points	0

Table 8.3. Results of deformation analysis between May 1991 and August 1992.

It should be mentioned that the global congruency test was close to detecting a 1.0 cm displacement in point number 17. If the confidence level had been chosen lower, significant movement could probably be detected there.

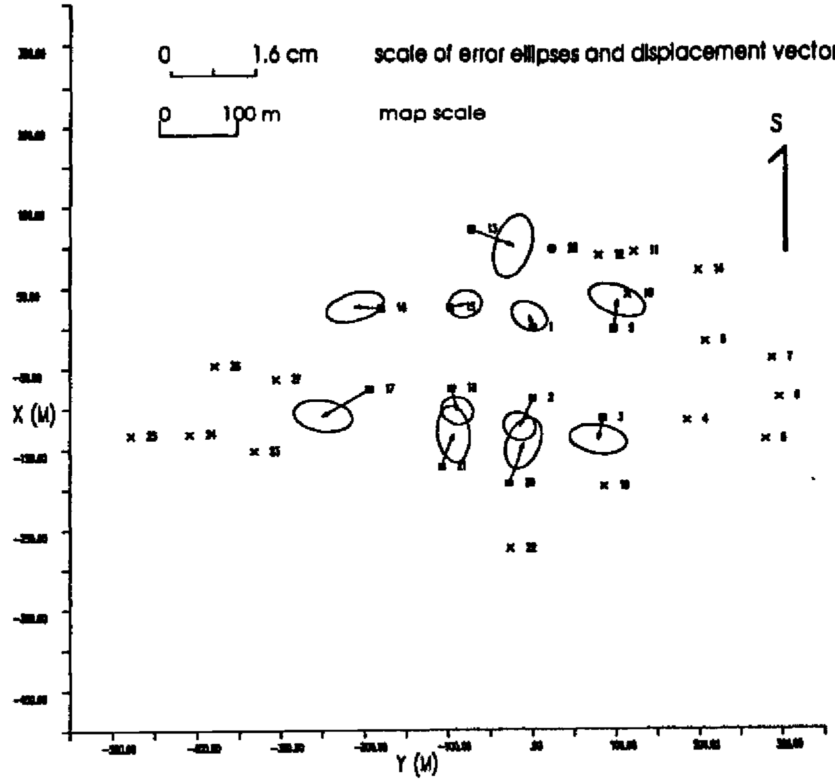

Figure 8.2. Movements in Puriscal between May 1991 and August 1992. Please note that south is upwards in this figure.

Considering the displacement vectors of this epoch, one can not see any dominant direction of displacements.

8.2.3. Displacement between March 1991 and May 1991

In this analysis the chances of detecting any movements are small. The identical points only cover the centre of Santiago de Puriscal and the error ellipses of the May 1991 network are big compared to the error ellipses of the March 1991 network. Adding to the low accuracy the time difference is only two months. The analysis shows this to be right as no displacement could be detected, i.e. the global congruency test showed the configuration of identical points in both networks to be the same

Number of identical points	12
Degrees of freedom	64
Standard error of unit weight	0.93
F-distribution value	1.74
Test value	1.73
Number of displaced points	0

Table 8.4. Results of deformation analysis between March 1991 and May 1991.

It should be mentioned here that the deformation analysis was very close to detecting a 1.1 cm movement in point number 13. If a lower confidence level had been used some displacement would probably have been detected.

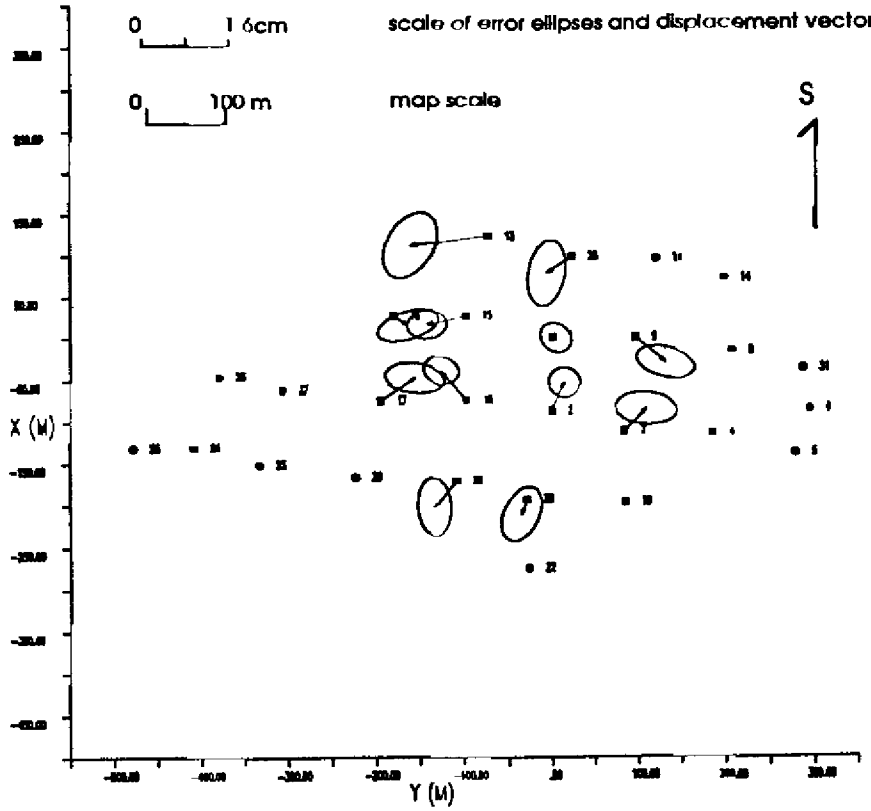

Figure 8.3. Movements in Puriscal between March 1991 and May 1992. Please note that south is upwards in this figure.

8.2.4. Results of deformation analysis in the plane

In the analysis seven points can be considered as displaced with the maximum of 1.4 cm, at point number 25, and the minimum of 0.4 cm at point 1. Those movements must be considered as very small. It is questionable whether this detected movement is a cause of the landslide or of something else, e.g. settlement of the soil. This movement is definitely not as big as the expected movement. Considering the fractures in the ground in and around the town of Santiago de Puriscal, the estimated internal movement was around 5-10 cm, at least.

If point 25 would be considered as standing still between the epochs, it can be concluded that the whole town is sliding down the slope approximately 1.5 cm per year. Some points, 1,3,4,5 and 9 then move more rapidly down the hill.

If the network in the town is considered as stable point 25 is moving in the opposite direction of 1,3,4,5 and 9. This does not fall in line with other sources concerning the movement of the Puriscal landslide.

8.3. Vertical displacements

For calculation of vertical displacements, the one-dimensional module (1-D) of the PANDA program was used. The module deals with one free parameter, namely translation of levels (Z). The confidence level 95% was used for the calculations, as well as a full covariance matrix. This to keep the same conditions as for plane displacements and to obtain maximum confidence.

The analysis was done for all combinations between the epochs, although the presentation has been concentrated to the 1990-1992 deformations. The reason for this is the comparatively low accuracy of the 1991 epoch. The overall displacements are also so small that maximum time interval is requested for movement studies.

The same points are used for all epochs, with a few exceptions due to destroyed points and gross errors.

The distribution in time of the epochs is seen in the following figure.

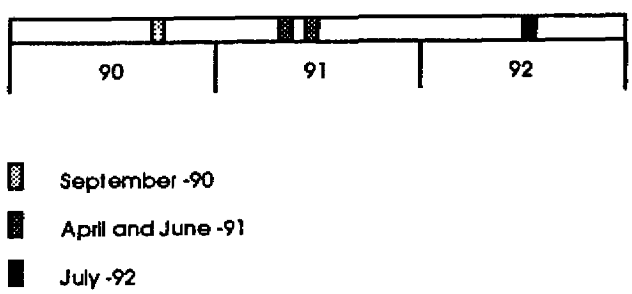

Figure 8.4. Time distribution for vertical observation epochs.

The terrain model and topographic map have been constructed by the program SURFER. Level values between the points are interpolated, so the figures are only to be taken as an illustration of the overall tendencies. The technique of the program is described in chapter 7.

8.3.1. Displacement between September 1990 and April-June 1991

This interval contains a comparatively large movement. Since the test value is considerably larger than the F-value, the global congruency test shows that the movement is significant.

Point nr	Displacement (cm)	Sz (cm)
1	-1.02	0.08
2	-0.52	0.08
3	-1.37	0.09
5	-2.61	0.14
6	-2.55	0.15
8	-1.15	0.12
9	-1.74	0.09
13	-0.85	0.10
14	-1.66	0.13
15	-0.39	0.07
17	-0.32	0.06
18	-0.57	0.07
20	-0.61	0.09
21	-0.25	0.08
22	-0.67	0.12
24	0.43	0.09
25	-2.29	0.10
28	-0.40	0.09

Table 8.5. Displacements and standard errors for the points 1990-1991.

The following parameters were used:

Identical points between epochs	25
Degree of freedom	21
Standard error	1.29
Value for F-distribution	2.06
Test quantity	83.26
Moved points	18
Stable points	7

Table 8.6. Results of deformation calculation for epoch 1990-1991.

Table 8.5. presents the points where movement can be proved statistically. Note the large difference between the displacements and their standard errors (Sz).

The deformations reach their maximum values in the eastern and western parts of the measured area. A general tendency of sinking can be stated.

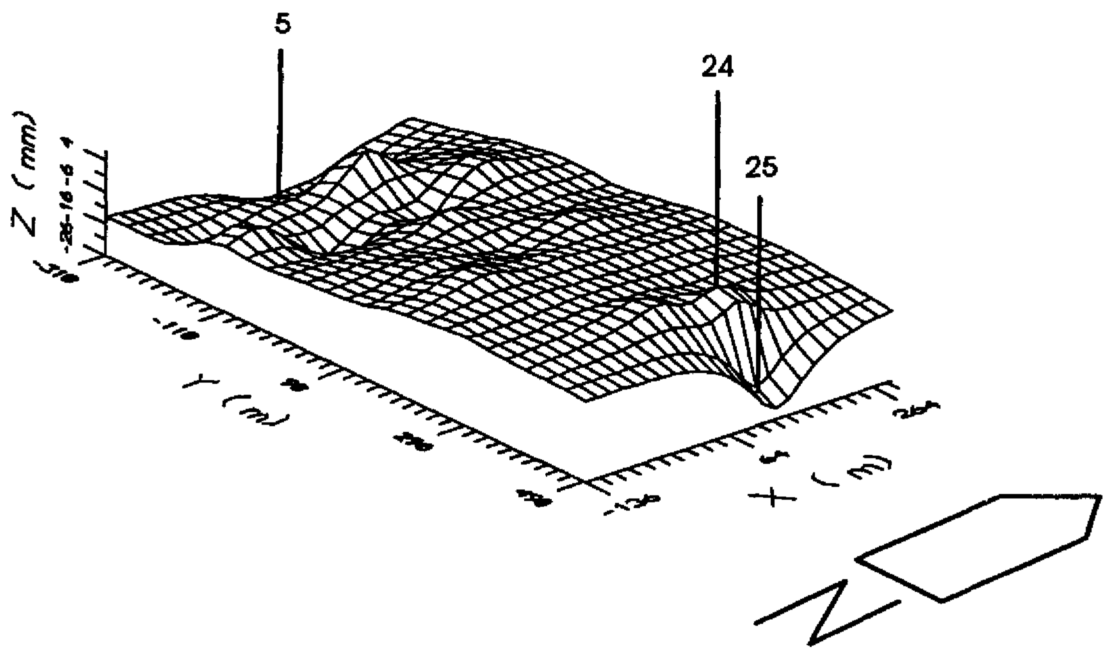

Figure 8.5. Grid model showing the deformations from 1990 to 1991. The points with the largest movements are marked.

8.3.2. Displacement between April-June 1991 and July 1992

Compared to the earlier interval, this contains considerably less movement. However, the displacement is significant enough to be determined statistically.

Normally, the PANDA program treats all points as stable until the process proves the opposite. A moved point gets object status, which means that it does not affect the datum of the network. If one wants to give this status to a point in all cases, this can be noted in the program prior to the calculations. In the PANDA program, this is done by attaching a symbol to the point in the co-ordinate file.

For this interval, two tests were made. The first one treated all points as datum defining, while the second test had object status given to four points; 5, 6, 14 and 22. They are points with only one connection to the other points in one or both of the concerned networks. Therefore, the mentioned points only played a passive role in the adjustment. This means that their standard error is only estimated by the program from the given accuracy of the instrument and the distance for the observation. The latter is considered since large distances involve more single observations and thereby less accuracy.

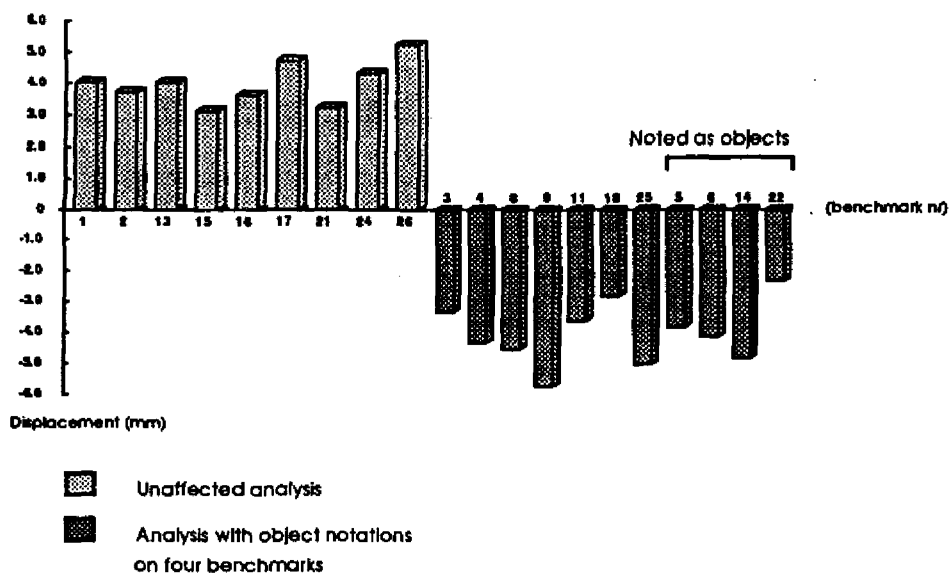

Figure 8.6. Displacement of object points for the two analysis methods mentioned in the figure.

The reason for that object notations were used for this interval and not the others was that 5, 6, 14 and 22 otherwise got stable status. This was not the case for the other intervals. It proved from comparing with the first 1991-1992 test that they greatly affect the whole general movement, as can be seen in figure 8.6. The sensitivity is caused by the generally small movement involved.

Further on in this thesis the unaffected analysis has been used. However, it must be stated that the change in movement direction is not to be taken as definite, due to the circumstances described above.

The presented data concerns the first test (without object notations). The following parameters were used for the analysis:

Identical points between epochs	23
Degree of freedom	18
Standard error	1.29
Value for F-distribution	2.17
Test quantity	7.20
Moved points	14
Stable points	9

Table 8.7. Results from the 1991-1992 deformation analysis.

Point nr	Displacement (cm)	Sz (cm)
1	0.40	0.06
2	0.37	0.06
13	0.40	0.09
15	0.31	0.07
16	0.36	0.08
17	0.47	0.07
21	0.32	0.07
24	0.43	0.11
26	0.52	0.11

Table 8.8. Displacements and standard errors for the points 1991-1992.

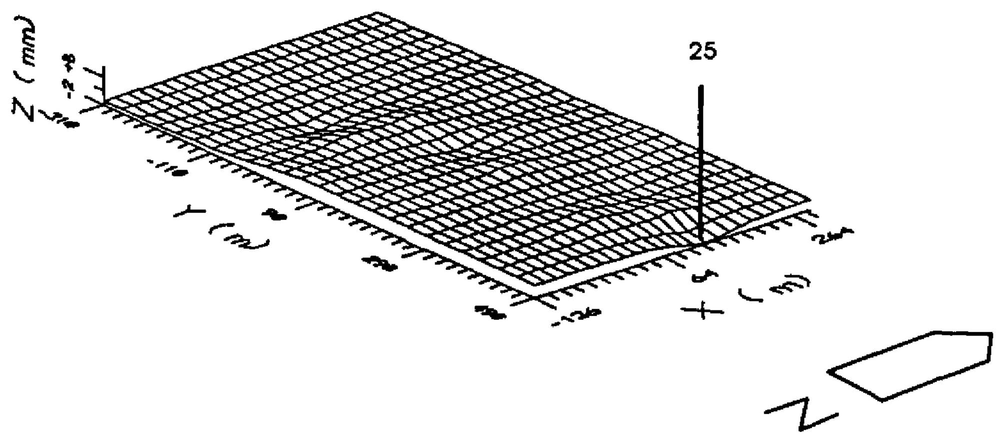

Figure 8.7. Grid model showing the deformations from 1991 to 1992.

The above figure in comparison with fig 8.5 shows clearly the decrease in movement from 1990 to 1992. It indicates that the movements basically occurred between 1990 and 1991. The figures have the same scale for the Z-axis.

8.3.3. Displacement between September 1990 and July 1992

As mentioned before, this interval contains the two most accurate epochs. Since the time interval is the largest obtainable, it is also the most reliable when looking at the long-time effects of the deformations of the measured area. The general movement is easily statistically determined.

The following parameters were used:

Identical points between epochs	24
Degree of freedom	19
Standard error	1.25
Value for F-distribution	2.12
Test quantity	522.34
Moved points	18
Stable points	6

Table 8.9. Results from deformation analysis of the 1990-1992.

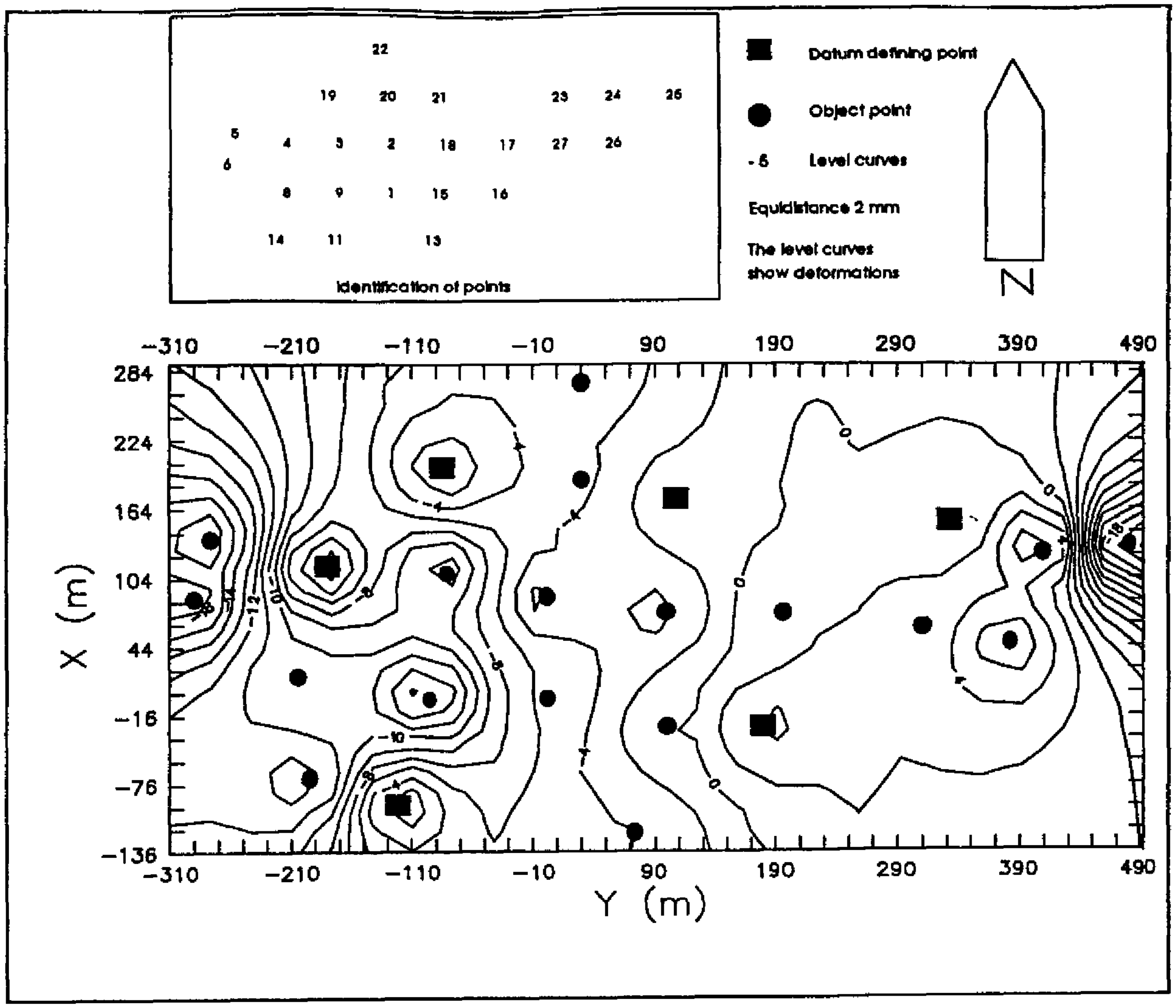

Figure 8.8. Topographic map of the deformations from 1990 to 1992.

The displacement level curves in the above map are interpolated by the program SURFER, which uses the Method of Inverted Distances as interpolation method. The displacements in between the points are unknown, but the interpolation gives an idea what the movements may look like if they follow the tendency of the known deformations. The determined stable points are given a zero displacement, since the movement is not statistically determined in their case.

Point nr	Displacement (cm)	Sz (cm)
1	-0.59	0.03
2	-0.13	0.03
3	-1.33	0.03
5	-2.61	0.05
6	-2.58	0.05
8	-1.22	0.05
9	-1.93	0.03
13	-0.42	0.04
14	-1.76	0.06
16	0.47	0.04
17	0.18	0.03
18	-0.47	0.03
20	-0.46	0.03
22	-0.53	0.05
24	0.89	0.06
25	-2.41	0.06
26	0.79	0.06
27	0.27	0.05

Table 8.10. Deformations and standard errors between 1990-1992.

All moved points have a greatly significant movement. Among the ones considered stable, points 11 and 21 have quite a big difference between the standard error and the displacement, which could be a sign of movement.

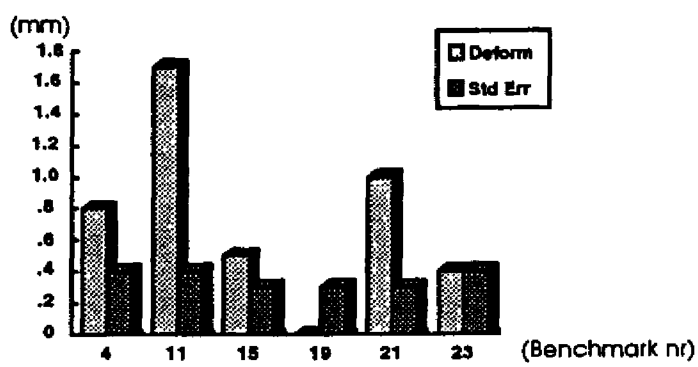

Figure 8.9. The displacements and standard errors of the stable points.

8.3.4. Interpretation of vertical displacements

Due to the accuracy of the precision levelling, movement could be detected for many points. The size of the movement is much smaller than expected though, as is the case for the plane displacements.

Another considerable detail is the differences between 1990-1991 and 1991-1992. The first interval shows a much larger movement, mostly due to small displacements in the latter. The two intervals also show movements in opposite directions (downwards and upwards respectively). The first period has an average movement among the displaced points of -10.7 mm, compared to only +4.0 mm for the latter. This in spite of the shorter time interval for the 1990-1991 period.

A look at figure 8.8 shows that the large movements are concentrated to the eastern and western edge of the measured area. A look at a terrain model of the same area (figure 8.10) shows that the large displacements lie in fairly flat terrain, although both sides lie near extensive steep slopes, which are outside the measured area. Probably, the steep slopes has a rapid earth movement, and thereby affects the benchmarks close to them.

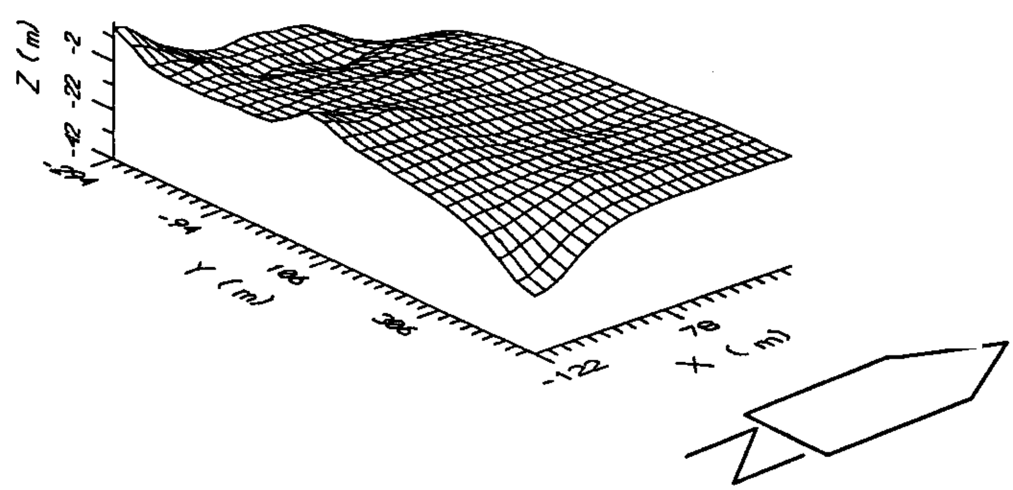

Figure 8.10. Terrain model made from known point co-ordinates and topographic map.

8.4. Conclusion of deformation analysis

Both the horizontal and vertical analysis show the largest displacements in the western and the eastern ends of the network. Most astonishing is the fact that the ends of the networks move in opposite directions. The western part moves towards W or NW, while the eastern part moves towards SE. The vertical difference shows that both parts move downwards. The movements are generally relatively small. In the plane they reach a maximum of 1.38 cm in the eastern part and 0.98 cm in the western part. The horisontal displacements can be explained by an active landslide. It should be noted that all displacements are relative to the centroid of the observed network.

Vertically there is a maximum displacement of -2.41 cm in the eastern part and -2.61 in the western part. The vertical displacements show a considerable decrease in movement from the first to the second epoch. The direction of the vertical movement changes as well, from sinking to a small uplift between the epochs. If this tendency is due to geological effects or just a coincidence can not be decided within the limits of this thesis. It is shown in chapter 8.3.2 that small errors in a few points can change the whole displacement tendency. Therefore, the change in vertical direction is not to be taken as definite. It should be considered when interpreting the displacements that they are relative to the centroid of the observed network

The found movements are very small compared to the expected displacements. Considering geological data, a movement of 4-10 cm was expected. The reason for such small movements can be the fact that Puriscal in 1990 suffered a seismic swarm. This seismic swarm might have reduced all tension from the ground, i.e. generated fractures. After this the observations were performed. Thus, during the interval between observations no tension builds up in the ground, as it was all eliminated during the seismic swarm.

Even though the found movements are relatively small, the conclusion that the landslide is not active, should not be drawn. Other researches indicate an active landslide (Mora, 1990). It is more probable that the small displacements found are due to a short observation period and an absence of observations to stable points outside the landslide.

9. Conclusions and recommendations

9.1. External control points

Given that the observations from March 1991 have a scale error, it is not possible to detect any significant movement of the external points. On the other hand if the original observations from March 1991 are correct, it is obvious that all the points have moved ≈ 0.5m towards the centre of the triangle they form. It can not be said which is the correct interpretation. Considering other indications, like fractures around the points, the experience of the OVSICORI personnel, no indications of errors in the DI3000 (the same in all three epochs), it is more likely that the displacements have occurred.

It would have been valuable if the DI3000 had been calibrated for scale error and not only addition error. This is needed for future observations. To be able to control which theory is correct, the points should be measured again during 1993 and a site investigation be done.

The town network has to be connected to fixed external points. If this is impossible with conventional methods, GPS (Global Positioning System) observations could be a solution if equipment for this can be obtained. In such case, external control points outside the landslide are not needed. Instead, some chosen points in the town network are measured with GPS equipment relative to a fixed point. This point does not have to be located within visible reach from the town and can therefore be located safely outside the landslide. The chosen town points thereby obtain absolute positions, which in turn gives the town network an absolute deformation status.

9.2. Town network

Both the horizontal and vertical analysis show the biggest displacements in the western and the eastern ends of the network. Quite astonishing is the fact that the points situated in these parts of the network move in opposite directions in the planar case. As the western part moves towards W or NW the eastern part moves towards SE. The vertical displacements are generally negative and show that both network ends move downwards.

The movements are generally relatively small. In the plane they reach a maximum of 1.38 cm in the eastern part and 0.98 cm in the western part.

Vertically there is a maximum displacement of -2.41 cm in the eastern part and -2.61 in the western part. The movements are statistically significant.

The found movements are very small compared to the expected displacements. Considering geological data, a movement of 4-10 cm was expected. The reason for such small movements can be the fact that Puriscal in 1990 suffered a seismic swarm. This seismic swarm might have reduced all tension from the ground, i.e. generated fractures. The observations were performed after the swarm. Thus, during the interval between observations no tension builds up in the ground, as it was mostly eliminated during the seismic swarm.

A contradictionary fact is the decrease and change of direction in vertical movements from 1990-1991 to 1991-1992. They may be the result of settlements caused by the seismic swarm. Another possibility is the effect of the rain season. The local people in Puriscal confirm that the movements of the main landslide is faster during the rainy season (Wolgé, 1991). The reason for this may be the changes in ground water level and pore pressure during rain season.

A look at the deformation intervals for the vertical displacements show that they are made during different climate conditions. The first interval contains the major part of the rain season and terminates in the middle of the dry season. The second interval starts at the same time and finishes the next year in the beginning of the rain season. These conditions may have affected the results.

As the found displacements are relatively small, they could quite well be due to settlements in the ground and not an effect of the landslide nor the above mentioned reasons. Another source of displacements could be the fact that the points in the town are located in concrete pavement blocks. The concrete blocks do not necessarily move locally in the same direction as the landslide. This can mean that the blocks show the wrong movement. It would be of significance if this could be investigated further.

Even though the found movements are relatively small, the conclusion that the landslide is not active, should not be drawn. Other research indicates an active landslide (Mora, 1990). It is more probable that the small displacements found are due to short observation period and absence of observations to stable points outside the landslide.

The internal movements on the top of a landslide are very small compared to its total movement. This statement of course is only valid for big landslides of the Puriscal type, as smaller landslides probably would show bigger internal movements.

It can be concluded that the method used for deformation analysis was found to be very well suited to do this kind of study. The method could detect, with a high level of significance, displacement smaller than the a priori standard error of the used measuring devices. This type of analysis is to be recommended for all types of deformation studies.

Recommendations for future studies :

- The intervals between observations have to be longer to be meaningful. With longer intervals the movements are possibly bigger and thus easier to detect and interpret. This will in turn allow reliable tension studies. In this study the displacements detected were not significant enough to do tension analysis.

- Observations during more epochs would make the analysis of displacements more secure, and it would be possible to detect tendencies as acceleration and velocities of landslide movements.

- Stable external points should be established in order to obtain the absolute movement. Then it would be possible to estimate the velocity and even the acceleration of the landslide in the town area. To obtain absolute deformations, GPS is an interesting opportunity. However, GPS is not suitable for the internal town measurements, as the accuracy is lower than conventional methods for short distances.

- The objectives of the measurements in Puriscal must be more clearly defined prior to the consideration of the different opportunities. If e.g. relative deformations are sufficient, the time and cost consuming absolute measurements can be avoided.

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