High-Strength Geogrids Bridging a Sinkhole: First Project Worldwide Including Renewed Sinkhole Activity

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ABSTRACT: In 1993 a critical huge sinkhole funnel in a karstic area on the German Federal Highway B180 near Eisleben was bridged and secured for the first time in Germany using extremely high-strength low-strain geogrids. Philosophy, design and construction of the high-strength geogrid solution are described. In October 2001 the sinkhole funnel re-opened. The geogrid system hold the road for over one hour, which was enough to stop the traffic. The solution proved to be successful in preventing disasters of this type. It is the first case known when a geogrid sinkhole-bridging was tested by real life.

KEY WORDS: Sinkhole, Void, Embankment, Road, Geogrid.

1 INTRODUCTION

For a long time the village of Neckendorf, south of the town of Eisleben in Germany, has been the repeated object of intense interest. This was prompted by a series of spectacular sinkholes and secondary ground failures near and on the German federal highway B180 (previously called F180). In June 1987 a big sinkhole (the funnel was over 15 m diameter at the surface and 25 m deep), caused the complete destruction of the road across its whole width and the closure of the unsafe length of road. The sinkhole was backfilled soon after the incident and a temporary diversion built. The increase in traffic levels after the German reunification and the generally unsatisfactory situation with regard to a temporary diversion prompted highways authority to start planning the safe reopening to traffic. Bridging the sinkhole with a geosynthetic solution was put forward as the preferred option. The German Federal Highways Office (the Bundesanstalt für Strassenwesen - BASt) approved and confirmed this decision in 1992. This prepared the way for the first use in Germany of geosynthetic reinforcement for bridging a sinkhole.

2 PHILOSOPHY, CONCEPT AND DESIGN OF THE SINKHOLE BRIDGING STRUCTURE

The top layers of the affected zone consist of around 160 m of thickly-bedded soils; mainly silts and clays, gypsum, anhydrite and limestone. Pronounced leaching effects are present particularly in the so-called Zechstein layers, with cavernous gypsum sometimes with open voids, residue from leaching (“ashes”) and seepage deposits. Numerous depressions and minor sinkholes with some major sinkholes are typical for this karstic region. The structure of this type of sinkhole can be simplified to a large cavern deep underground, a vertical chimney passing upwards from the cavern and a much wider sinkhole funnel on the surface.

2.1 An Engineering View of the Problem

The problem is the result of the natural process; the formation of a cavern deep underground – the chimney extends upwards – and a sinkhole funnel appears at the ground surface. After filling a chimney and funnel there is always the risk of secondary failures because the leaching processes in the caverns continue. A prognosis at any particular time cannot be given.

The only engineering solution in such cases is to neutralize the consequences of the sinkhole for the road on the surface. The sinkhole funnel can form in a relatively short time. In 1987 the B180 road at Neckendorf near Eisleben was destroyed by such a major sinkhole, which occurred as a result of the above phenomenon.

The road collapsed over its whole width. The layers in the lower section of Zone 1 collapsed first followed by those in Zone 2 due to further subsidence (Fig. 1). In 1987 the crater was completely filled with loosely placed imported stone and sand. However, there was no information about the density and stability of the failed soils and the new fill material in the sinkhole, nor about the water flows in the caverns deep underground. Therefore the important traffic route B180 remained closed on safety grounds until 1993. A temporary diversion had to be used.

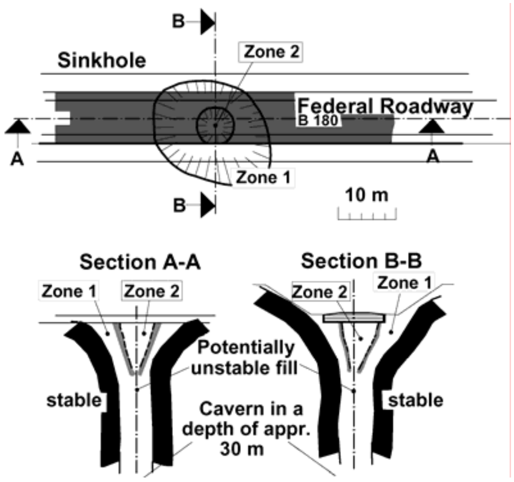

Figure 1. Geometry and potential sinkhole zones under the B180.

2.2 Concept and Philosophy of the Reconstruction

In 1992, the regional highway authority decided that the 1987 temporary diversion was no longer acceptable. Based on the history of the sinkhole and the measurements taken after filling, it did, however, seem plausible to predict that there was a higher probability of fresh failures (secondary subsidence) in the smaller Zone 2 and a lower probability of fresh failures in the larger Zone 1. The worst-case scenario would be a catastrophic failure of the whole chimney and with it Zone 1 (Fig. 1). There were mainly two possible solutions under discussion: a bridging reinforced concrete slab ("hidden bridge") and, for the first time in Germany, a geosynthetic-reinforced soil solution. The reinforced concrete slab was discounted mainly due to one decisive reason: the brittle failure mode in the event of the ultimate load capacity being exceeded ("brittle failure without warning").

Therefore the concept of a innovative solution involving a heavily geosynthetic-reinforced gravel cushion was preferred. This system would retain its load-carrying capacity and remain fit for use up to a very large deformation. Approaching failure, it is ductile rather than brittle and thus would undergo a "failure with warning" after an adequate time period and in a suitably safe manner.

The final safety philosophy and concept included the following significant key characteristics and requirements:

- The primary consideration was the safety of the driver and the vehicle traveling at up to 100 km/h right where a new large sinkhole opens (Zone 1, Fig. 1). The longitudinal and transverse deflections (or bending or settlement) of the carriageway had to be kept within acceptable limits and the carriageway should not crack or collapse locally over the underlying gaping "large" funnel (Zone 1, Fig. 1). No sharp edges / steps should form on the carriageway.
- The system would have to safeguard the traffic in this way for a short time only (10 minutes at the most). This limit arose partly for safety and engineering reasons (it was a new first-time application in Germany), but above all for economy.
- Within the 10 minutes period, a detection and warning system should stop the traffic in both directions at a distance of several hundred meters by means of automatic stop signs.
- The area to be protected was located in a cutting with the effect that only a flat, thin, geosynthetic-reinforced cushion placed almost directly under the road construction could be considered. The solution would involve the minimum of excavation and fill.
- In the worst case, the solution would have to

bridge over a funnel with a diameter of up to 15m (!).
- In this worst case, the relative deflection of the carriageway (ds/Ds in Fig. 2) should not exceed 0.06 – 0.07.
- The project, the first such in Germany, represented a major and unique engineering challenge, as it would even today.

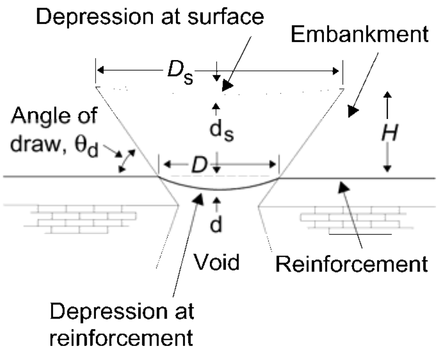

Figure 2. Analysis model in accordance with BS 8006 (BSI 1995).

The BS 8006-method (Fig. 2) was preferred due to different reasons (Alexiew 1997, Alexiew and Thurm 2003). Further details of the model and analysis can be found in BSI (1995). Generally, a geogrid was preferred as reinforcement (instead of e.g. a woven geotextile) mainly due to its higher coefficient of interaction (bond) to the soil.

The determination of the design strength of the reinforcement was carried out in accordance with the requirements of the German Guidance Note (FSGV 1994), which was only available in draft form in 1993. The analysis, the polyvariant calculation with various load cases and variations of other properties showed that a uniaxial low-creep geogrid with a mobilisable tensile force in the roll-out direction (or "machine direction" - MD) of 1200 kN/m at ≤ 3.0 % strain and 600 kN/m at ≤ 1.5% strain (short-term) would be required. More detailed explanation regarding the design and the engineering background for the final solution (Fig. 3) can be found in (Alexiew and Thurm 2003). Geosynthetic reinforcement with these properties was not yet available in 1993.

Thus, a new geogrid had to be developed for this project with extreme strength, high tensile modulus and low creep. The choice was a yarn made from Aramid®. A five meter wide uniaxial geogrid was specially developed, manufactured and tested. A world first! The typical tensile force/strain graph (short-term) in the machine direction (MD) is shown in Figure 4.

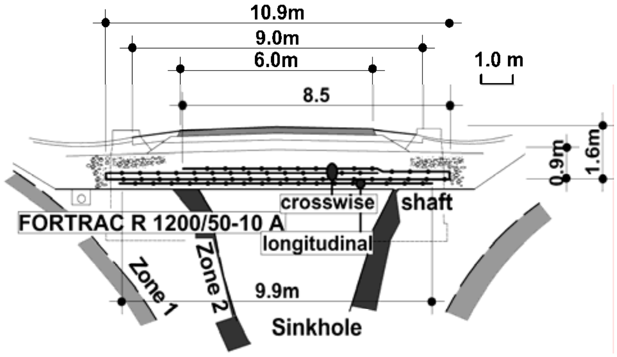

Figure 3. Schematic cross-section of the sinkhole bridging system.

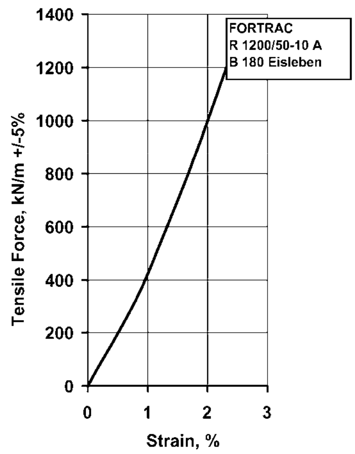

Figure 4. Tensile force/strain graph for the Fortrac® 1200/50-10 A.

Figure 5 shows a plan view of the geogrid reinforcement (simplified execution drawings from (HUESKER 1993) and the warning system. A high-quality clean well-graded gravel (soil classification GW) within the 0.1/56 fraction was specified for the material for the reinforced gravel layer. It required to be compacted to a relative Proctor density of Dpr ≥ 103% in order to ensure good mechanical properties and the composite action of the gravel-geogrid-system.

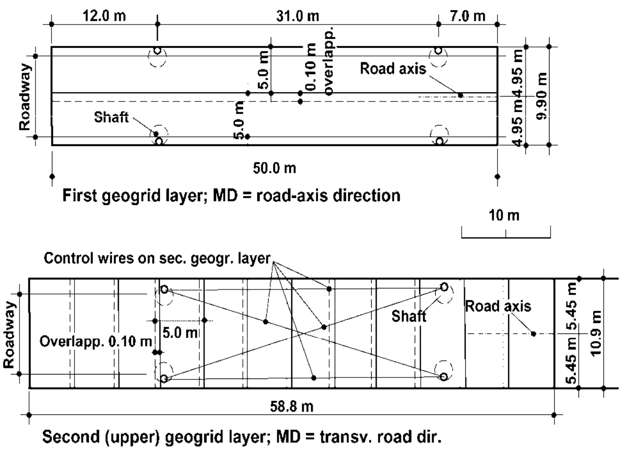

Figure 5. Simplified layout of the reinforcement and the warning system.

If the movement of the ends of the wires indicates a settlement of the reinforced soil structure equal to a strain of 1.5% in the geogrid, a warning system comes into operation and traffic in both directions is stopped at a safe distance on both sides of the critical area by electronic warning signs. The warning system was designed to be activated before the complete opening of the "large" Zone 1 (Fig. 3).

3 EXPERIENCES DURING AND AFTER CONSTRUCTION STAGE

The geogrids were supplied prefabricated in the placement lengths required by the design. The flexibility of the geogrid and its relatively low weight per unit area (high specific strength) meant that handling was easy and a small team was able to install the geogrid on site.

A cross beam was used to install the geogrid. It had already been realized that for bridging sinkholes, it was most important for the geogrid to be tighten, as even the best high-modulus geosynthetic reinforcement loses efficiency if it does not immediately reacts (activates) as a result of improper placement (Alexiew et al. 2003).

The entire system over a length of about 60 m (Fig. 5) was constructed in a week in October 1993. The section of the B180 was back in operation in October 1993 (Fig. 6). The road had been deflection monitored ever since using the measurement and inspection chambers (Alexiew 1997, Alexiew and Thurm 2003).

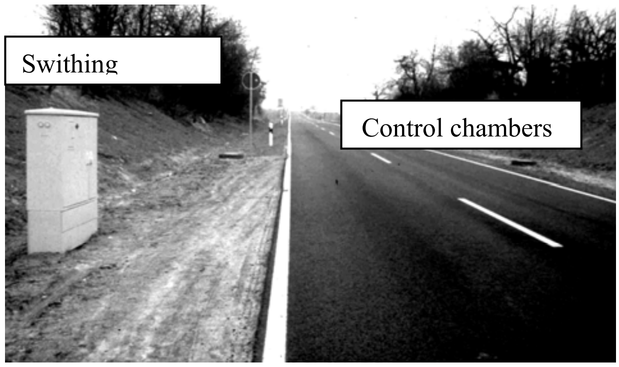

Figure 6. B 180 after completion: half of reinforced zone, chambers and cabinet.

4 RENEWED SINKHOLE ACTIVITY IN OCTOBER 2001

Between 1993 and 2001 any settlement of the carriageway was visually monitored at regular intervals and the sensors attached to the wires in the warning system inspection chambers were checked for any displacement. No deformation was detected in eight years of monitoring. The mechanics and electrics of the warning system were inspected and maintained.

Then on 17.10.2001 (eight years after the construction of the sinkhole bridging system) there was something to measure: Renewed sinkhole activity and reopening of the sinkhole funnel under the B180.

What follows is the chronological reconstruction of the events according to eye-witness statements of the occupiers of the allotments near the protected zone.

- About 18:00: The first noises from the side slopes, which were starting to move (area in cutting, see above). A sinkhole funnel appeared in the slope to the east of the protected zone. The traffic on the B 180 continued to flow.
- About 18:30: Settlement on the carriageway surface could now clearly be seen. At this point in time many vehicles were still passing over the site at undiminished speeds of 100 km/h. The warning system, which was intended to stop traffic in both directions at a safe distance away in the event of increased deflection (settlement) (see above), did not react.
- About 18:45: The deformations continued to increase and affected a very large area. The

local people managed to stop the traffic and informed the authorities. The warning system did not react.

- About 19:00: One hour after the start of renewed sinkhole activity, the whole of the carriageway area was undermined and the cutting slope to the west side of the road collapsed. The sinkhole funnel was already bigger than the width of the reinforced system including the trenches (12 – 13 m), i.e. the "large" Zone 1 (Figs. 1 and 3) had collapsed. The carriageway was severely deformed but was still intact as a whole unit.
- About 19:30: The sinkhole funnel had greatly increased in size in all directions. The carriageway is severely deformed but is still "standing" as a whole unit. At this point the soil structure had been bridging an irregularly-shaped sinkhole funnel with a diameter estimated to be between 12 and at least 15 m for more than half an hour. One and a half hours had elapsed since the renewal of sinkhole activity. Shortly after 19:30, the carriageway collapsed (i.e. including the geogrid) over the increasingly widening sinkhole and fell into the funnel, which had also increased in size . For understandable reasons it cannot be said with any certainty whether the diameter was 16 or 18 or 20 m. Investigations would not reveal whether the reinforcement tore exactly in the middle of the funnel. The system's anchorage zones under the road in front of and behind the funnel remained intact.

5 THE DAY AFTER

Next morning the irregularly-shaped funnel had a diameter of over 20 m (Fig. 7).

It cannot be clearly established whether and by how much the hole in the carriageway (on the previous evening) had grown after the failure. Its position corresponded with the estimated position of Zone 1 in 1993 (Fig. 1). It was obvious that the bridging system had more than met the requirements and expectations of the 1993 design and construction in terms of load carrying capacity, deformation and behaviour over time. This was all the more crucial as the warning system and the stop signs had not reacted. The following three main points were now of greatest interest: checks of the geogrid behaviour (or its current condition) and the anchorage zone and the answer to the question of why the warning-stop signs did not react (warning system).

5.1 Geogrid and Anchorage

Several square metres were cut out and recovered from the various geogrid layers before being tested.

Visually the recovered geogrid appeared to be in very good condition, even near the tear site. The values obtained from the tests were compared with the records of the load-extension tests from 1993 of the newly manufactured geogrid. The only recorded change was a slight increase in the tension modulus but no loss of strength, even after eight years in the reinforced gravel layer under heavy traffic on the B180, with the geogrid very close to the carriageway surface and following loading to failure. The two anchorage zones under the road in front and behind the funnel had remained intact. The geogrid had not pulled out of them despite loading to failure over the funnel.

Tensile forces of at least 1200 kN/m would have been carried over a relatively narrow area. The wide cracks in the asphalt surfacing in the anchorage zone near the sinkhole funnel gave an indirect indication of the large loads on the area (Fig. 7, detail).

5.2 Warning System

The question of why the warning system and the stop signs did not operate was investigated in detail. The investigation revealed that the failure to react was not due to the (simple and reliable) design concept nor to the construction of the warning system but rather that at the last inspection two weeks earlier someone had forgotten to switch the power back on to the electronics.

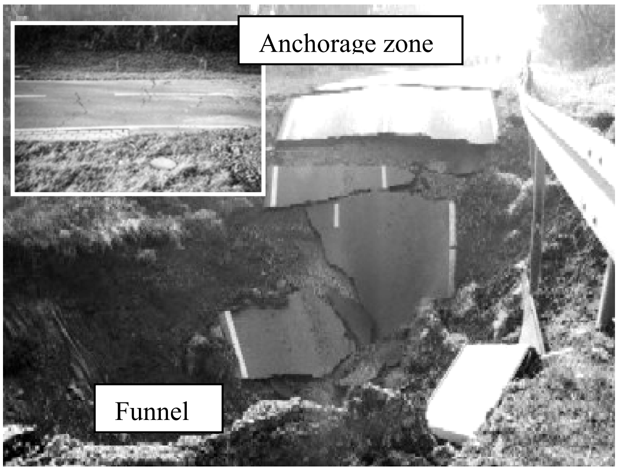

Figure 7. View the morning after the renewed sinkhole activity.

7 FINAL COMMENTS AND CONCLUSIONS

Upon the reopening of the sinkhole, the first sinkhole bridging system incorporating geosynthetic reinforcement to be conceived, designed and constructed in Germany functioned better than predicted: it bridged a sinkhole that was larger than the design requirements for longer than was required. The 1993 system had been correctly planned, designed and constructed. The events proved the philosophy of a "ductile failure with warning", upon which the project had been based. The bridging of an oval funnel with one-way spanning reinforcement is possible and functions well with proper design and implementation. A flat soil-geogrid bridging system, laid close to the road surface can be feasible and will function correctly with suitable choice of design and reinforcement. The first project in the world to incorporate an Aramid® geogrid (in this case with a short-term strength of 1200 kN/m) was proven in practice. The method of analysis and design of sinkhole bridging systems in accordance with (BSI 1995) is sufficiently correct at least for relatively thin bridging layers using non-cohesive soils; the same applies for the "elastic rope / membrane theory". If reliance is placed on warning systems, it should be the aim to eliminate human involvement technically or logistically as much as possible. And: the project forming the subject of this paper considers a very rare event – the occurrence of the "worst case design scenario" (somewhat like the 1 in 100-year earthquake). As far as is known, this is the first time a sinkhole bridging solution has been tested in real life.

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