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# Stability of minestone used as artificial bed material to compensate for bed subsidence caused by mining on the River Rhine

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ABSTRACT: An extensive study of the historical development of the Rhine River reach was considered and numerical simulations of the bed development were performed to assess the long-term stability of minestone added as an artificial bed material to compensate for bed subsidence caused by mining. A large-scale campaign of in-situ measurements was carried out in addition to laboratory studies. The predictions of a one-dimensional sediment transport model showed that mining activities between 1934 and 1975 had caused the bed to subside by up to 3 m. The predicted changes in the bed level from 1975 to 2000 showed that, without compensation, further bed subsidence of up to 2.5 m would have occurred. The minestone exhibited a generally high tendency to weathering in hydraulic and geotechnical laboratory investigations. Furthermore, the results revealed that in-situ investigations of the river bed over several metres were essential for a final stability assessment. Evidence of the mobilisation of deeper layers of minestone during floods is provided by freeze core and drill core samples in which the minestone was arranged more or less randomly. Only around 70 percent of the minestone material still located in the river bed is available.

*Keywords: Mine stone, Bed subsidence, Bed stability, Sediment transport, In-situ investigations*

## 1 INTRODUCTION

### 1.1 *Background*

The decision to close the Walsum mine in mid-2008 prompted the German Federal Waterways and Shipping Administration (WSV) to prepare forecasts for the future stability of the riverbed in the relevant section of the Rhine River and to initiate any required stabilisation measures. The aim of the WSV is to design the stretch of the Rhine River affected by subsidence in such a way that its morphological and bed stability characteristics behave in a more or less similar way to the adjacent river sections immediately up- and downstream.

Since the 1930s the coal industry in the Duisburg area has also operated under the Rhine River and its flood plains. Whereas no compensation of the mass losses caused by subsidence of the riverbed took place until 1976, the losses have since been compensated by adding minestone (a by-product of coal mining) as an artificial bed material in the area of the Walsum mine. The compensation measures were carried out promptly in the section of the Rhine between km 795 and 807. Today, as a result of the subsidence, the riverbed is composed of minestone material that locally reaches several metres in thickness.

### 1.2 *Task*

The investigation into the long-term stability of the supplied minestone was split into four stages (BAW, 2007b):

- Chronological study and investigations of the development of the stretch of the Rhine River under consideration (Rhine-km 775 to 814) since 1934.
- Experiments on the typical material properties, stability properties and weathering behaviour of the minestone under flow stress.
- Numerical simulations of the evolution of bed levels for various boundary conditions using a one-dimensional numerical model.
- Field investigations to determine the bulk behaviour of minestone and the storage characteristics of the site.

## 2 INVESTIGATIONS

### 2.1 *Overview and chronological study*

A study was commissioned to expand our knowledge and data. Its aim was to produce a meticulous compilation and documentation of the historical development of the Lower Rhine River and its banks as a result of the mining industry's operations since 1934. The anthropogenic impacts of mining and of the compensation measures on the flood plains were documented as part of the study.

The large-scale and long-term developments on the stretch of the Rhine River between km 775 and km 814 during the period from 1934 to 1975 were examined in a preliminary study. A subsequent detailed study focused on the developments in the core area of the subsidence caused by mining (Rhine-km 795 to 807) since 1975. Since 1976 the mining-induced mass losses have been compensated for in this area by using minestone as an artificial bed material added by means of dumping vessels.

The information and documents available on the mining-induced problems under the relevant section of the Lower Rhine River were comprehensively described as part of the studies. The extent to which they contribute to the understanding of the historical and current morphological processes has also been established. Finally, the areas in which information and knowledge deficits exist were stated.

The procedures and developments on the stretch of the Rhine River between Rhine-km 795 and Rhine-km 807, which is directly influenced by the mining activities of the Walsum mine, since the beginning of the minestone supply (1976) were analysed in detail and accounted for in terms of volume differences wherever permitted by the available documentation.

Although a final estimation was not possible due to a variety of uncertainties, the analysis at least confirmed that a successful strategy is being pursued by the current supply mode. Balancing uncertainties are due to neglecting the deposits along the embankments or on the flood plains as well as the decay and suspension of significant proportions of minestone. The study recommends performing field measurements in order to obtain more detailed information on the grain size spectrum evolving at the bed of the Rhine River under bottom shear stress.

### 2.2 *Experiments*

The analysis performed in the geotechnical laboratory at BAW showed that the minestone generally has a high tendency to decompose (see Figure 1) by breaking along the fissures, even under slight mechanical loads.

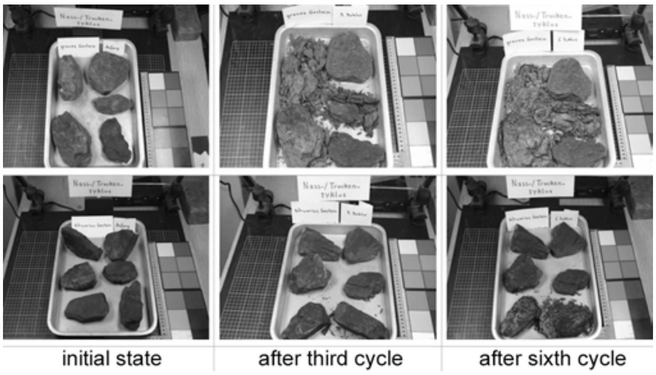


Figure 1. Alteration of minestone due to wet and dry treatment (Upper row "grey", lower row "black" fractions)

Generally speaking, the minestone material can be characterised as shale or mudstone. The material, which has a more or less pronounced stratification, contains a high proportion of graphite and is partly composed of fine sand or small proportions of marl. There are two different forms, each with partially heterogeneous behaviour:

- The black or dark grey rock material contains a great deal of graphite.
- The light to medium grey rocks have a less pronounced stratification. The graphite content is lower and the proportion of plant material remains high. It is less stable than the black material.

The coefficients for the minestone obtained in the Micro-Deval test according to EN 1097-1, in which the abrasion resistance of rocks is determined in a rotating cylinder under defined conditions, were roughly ten times higher than for the naturally prevailing Rhine River gravel (see Table 1). The amount of wear observed in the investigations with the abrasive wheel according to Böhme (DIN 52108) was approximately five times higher than for gravel.

Table 1. Results of the Micro-Deval test according to EN 1097-1

| Grain fraction | Micro-Deval coefficient | |
|---|---|---|
| [mm] | mine stone | gravel |
| 10 – 14 | 81 | 8 |
| 4 – 6.3 | 94 | 12 |
| 6.3 – 10 | 91 | 12 |
| 8 – 11.2 | 91 | 10 |

The investigations performed at the hydraulic laboratory of the University of the German Armed Forces in Munich (UniBW) studied the bed stability, sediment transport characteristics and intermixing behaviour of Walsum's minestone in particular.

The flume studies conducted in a laboratory channel with sieve curves downsized by a factor of four (see Figure 2) showed that the minestone in its supply-specific composition ($d_{50} \cong 50$ mm; over 90 % with d > 20 mm) behaved differently from the natural Rhine River material ($d_{50} \cong 14$ mm; around 40 % with d $\cong$ 20 mm). In addition to the larger grain size, the predominantly flat grain shape, which favours the formation of imbricate structures, at first sight provides greater stability and much lower minestone transport rates in its original shape compared with the Rhine River gravel.

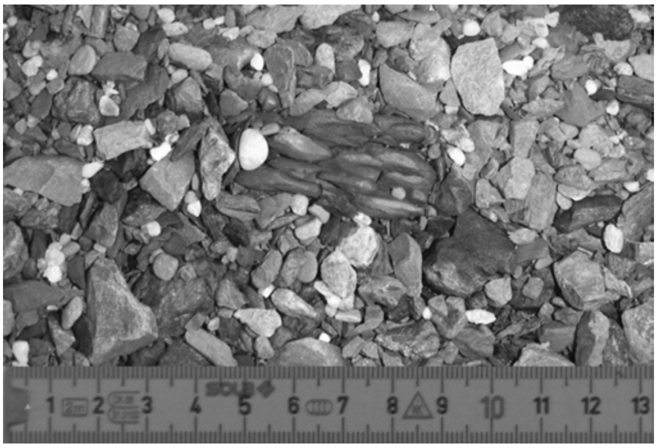

Figure 2. Mixed bed of mine stone and Rhine River gravel in the scale model of UniBW

In contrast to these findings there is a high probability that the original shape and particle size distribution will not be preserved under the actual conditions in the Rhine River. The tests on the material properties strongly indicate that a much finer grain distribution of the minestone will occur during the pouring process and when the minestone is in direct contact with the river bed and the bed load. Very fine particles are washed out and go into suspension but can hardly be detected due to the high degree of dilution in the samples of the river bottom or in the load measurements.

Owing to the high instability of the near-surface minestone, the intermixing behaviour also depends on the evolving grain distribution. It determines the extent to which minestone accumulates in the bed load and how much of the natural bed load will be stored in the matrix of the developing compound riverbed. As long as the minestone remains mobilised it is subject to the decay process described above with a tendency to be crushed fairly quickly between the significantly harder gravel particles.

The questions that remained unresolved after a series of experiments at UniBW indicated that the effect of decay plays a prominent part in the quantification of the results for the final assessment of the minestone stability problem. Hence, further long-term laboratory and in-situ investigations were considered essential to obtain substantiated statements on the long-term behaviour of the minestone in the bed of the Rhine River.

## 2.3 *Numerical simulations*

A one-dimensional numerical model for the Lower Rhine River from km 643 to km 865 was established by BAW to support the monitoring of sediment management along the free-flowing Rhine River. It was based on the HEC-6 computer programme in order to provide long-term and large-scale forecasts of the development of the mean elevation of the riverbed assuming various boundary conditions. The total sediment transport rate was determined by applying the Toffaleti formula (1969). In spite of certain code-specific constraints, it was also possible to use the model to predict the stability of minestone in the core area of the subsidence caused by mining (Rhine-km 795 to 807).

After a fine calibration, which focused on the area under investigation, the consequences of different intervention scenarios for the evolution of the mean level of the riverbed in the past, the present and the future were analysed. Specifically, the development of the mean riverbed level in the period from 1934 to 1975 was investigated under the hypothesis that no mining had occurred under the Rhine River. Furthermore, the morphological evolution was simulated under the hypothesis that no measures to compensate for mining subsidence had been undertaken since 1975.

Figure 3 provides an answer to the question of how the morphological development would have taken place during the period from 1934 to 1975 without any mining activities. The hatched area representing natural subsidence shows the impact of mining on the change in mean height (dotted line), with depressions of up to about 3 m in the core area of mining subsidence.

A direct comparison of the two calculation scenarios "occurred development (dotted line)" and "notional development if no mining had occurred (dashed line)" reveals that slightly retrogressive erosion above the Rhine-km 775 location was induced in addition to the erosion of up to about 2.6 metres (difference between dotted and dashed lines) caused in the core zone of subsidence as a result of the accelerated decline of the river bed.

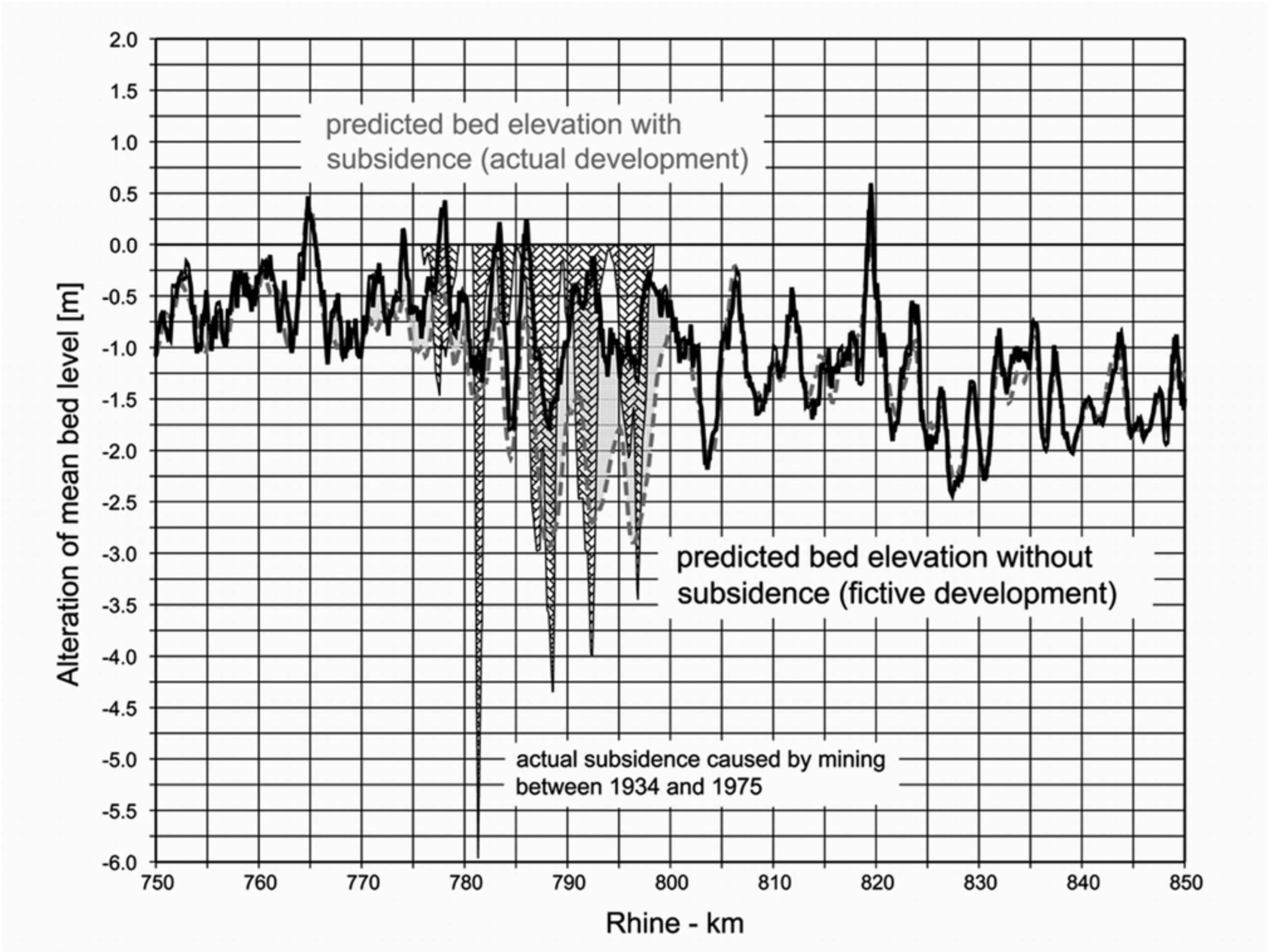


Figure 3. 1D-morphological model of the Lower Rhine River; prediction of subsidence-specific bed deformation caused by mining between 1934 and 1975

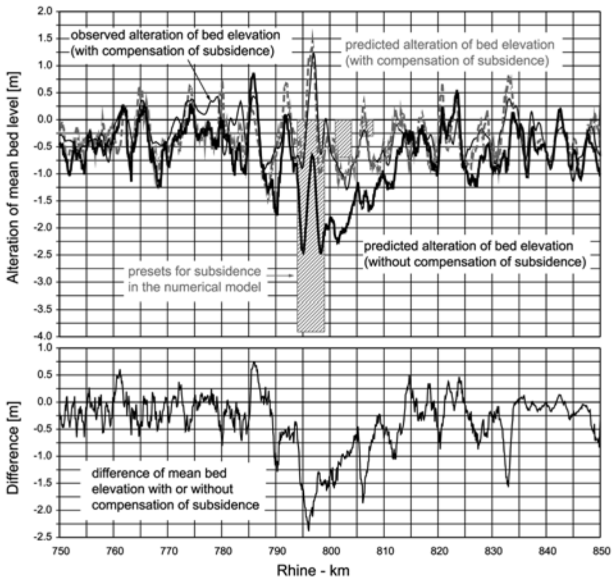


Figure 4. 1D-morphological model of the Lower Rhine River; prediction of bed deformation with or without compensation of the subsidence caused by mining between 1975 and 2000

The second scenario served to examine how the riverbed would have developed from 1975 to 2000 if the subsidence had not been compensated for by supplying minestone. It has been shown in this case (see Figure 4) that, without the compensation measures in the subsidence area, an additional depression of up to 2.5 m would have formed within a period of 25 years, representing an average annual depression rate of 10 cm.

A decline of this magnitude is neither intended for the use of the Rhine River as a waterway nor an acceptable situation in terms of nature conservation and agricultural aspects. Moreover, subsidence-induced erosion would have occurred immediately up- and downstream of the area affected by mining and resulted in a significant increase in maintenance requirements.

Owing to the high degree of complexity of the overall process, the one-dimensional numerical model cannot be expected to deliver detailed statements on the stability characteristics of the minestone. Nevertheless, thanks to the meticulous preparation of the input data and the detailed consideration of anthropogenic influences, the model provides an ideal basis for future investigations with the expanded and improved version of the HEC-6T computer programme and the more sophisticated two- and three-dimensional numerical models of BAW.

## 2.4 *Field investigations*

Against the backdrop of recent studies and findings it was essential to conduct sampling of the riverbed to a depth of several metres in order to establish long-term forecasts. It was assumed that selecting suitable sampling points in the supply area and downstream would enable reliable conclusions to be reached on how the actual process of weathering of the minestone is proceeding or has proceeded. Three field campaigns were therefore launched and their evaluation contributed substantially to resolving the remaining questions.

The first campaign aimed at reclaiming minestone from a fresh supply area. Four truck-loads of 800 tons of minestone each had been dumped in the stretch of the Rhine River between km 805.1 and 805.5 over a few days (2006-11-29 – 2006-12-01). The freeze core samples were taken immediately afterwards between 4$^{th}$ and 6$^{th}$ December. A further investigation was carried out by taking samples in May 2007. The primary objective of the campaign was to analyse the grain size evolution and the intermixing behaviour of minestone immediately after supply and during the medium-term follow-up.

As a direct comparison of the particle size distributions of the freeze core samples taken in December 2006 and those taken in November 2006 shows (see Figure 5) the minestone material is subject to degradation immediately after dumping. Although the analysed core samples show a relatively narrow particle size band, they contain a much higher sand fraction than the feedstock. The sand fraction increases from around 5 % in the feedstock sample to around 15 % in the samples taken in May 2007.

The comparison of the particle size distributions of the feedstock and the prospecting samples indicates that the sand fraction increases from around 5 % to a maximum of around 25 %, while there is no significant increase in the fine gravel fraction. The sand is composed of minestone and the natural river sand.

This initial rough analysis indicates that the mine stone is crushed and the river sand is able to settle in the cavities of the minestone layer. However, the lab report by BAW (2007a) states that the analysis of considerably more samples of further field investigations is recommended in order to achieve a better understanding of the processes and to gain sounder results.

The second campaign aimed to determine the medium- to long-term behaviour of the supplied minestone. Prospecting samples were taken and freeze cores of around 1.0 – 1.5 m in length were drawn between Rhine-km 793.0 and 808.0 in the period from April to May 2007.

Samples were taken within the 15 stations at each of the five positions in a cross-section (Rhine River axis (= axis ± 0), axis ± 50 m, axis ± 100 m) (BAW, 2008a).

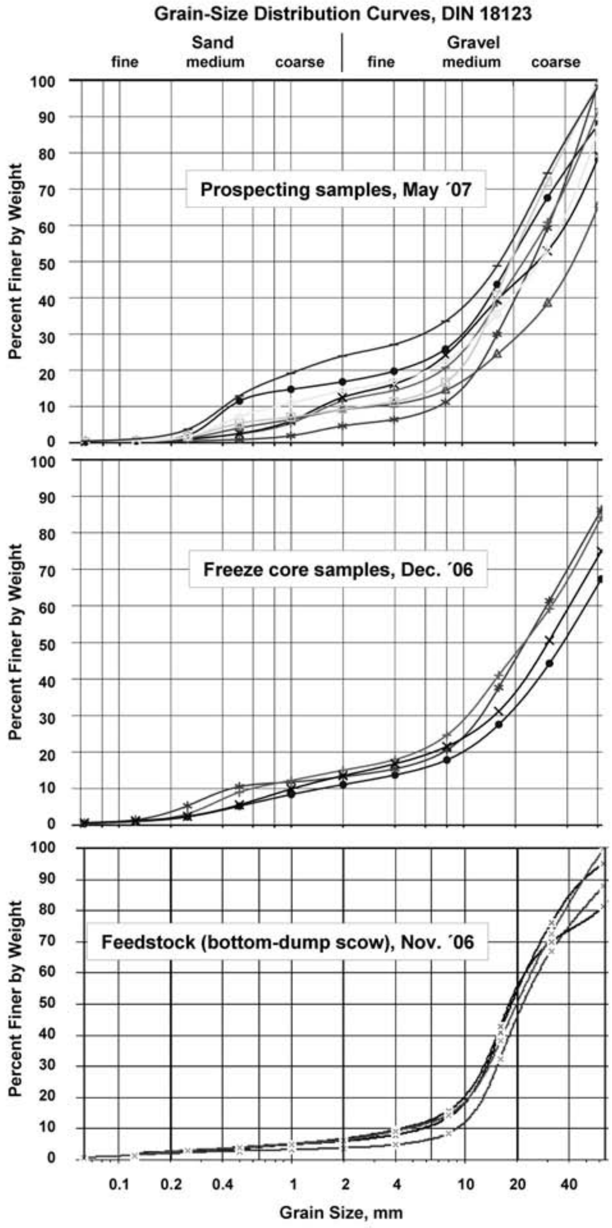


Figure 5. Temporal evolution of grain-size distributions from Nov. 2006 to May 2007

A typical preparation of the freeze cores is shown in Figure 6 for the five position samples of a cross-sectional profile. The proportion of minestone is indicated in shades of grey by the marks in the background of each sample: the darker the shade (black corresponds to 100 %), the higher the proportion of minestone. A detailed soil identification was performed and the selected values were added by linear interpolation in order to determine the total amount of minestone within the range considered for each sample unit.

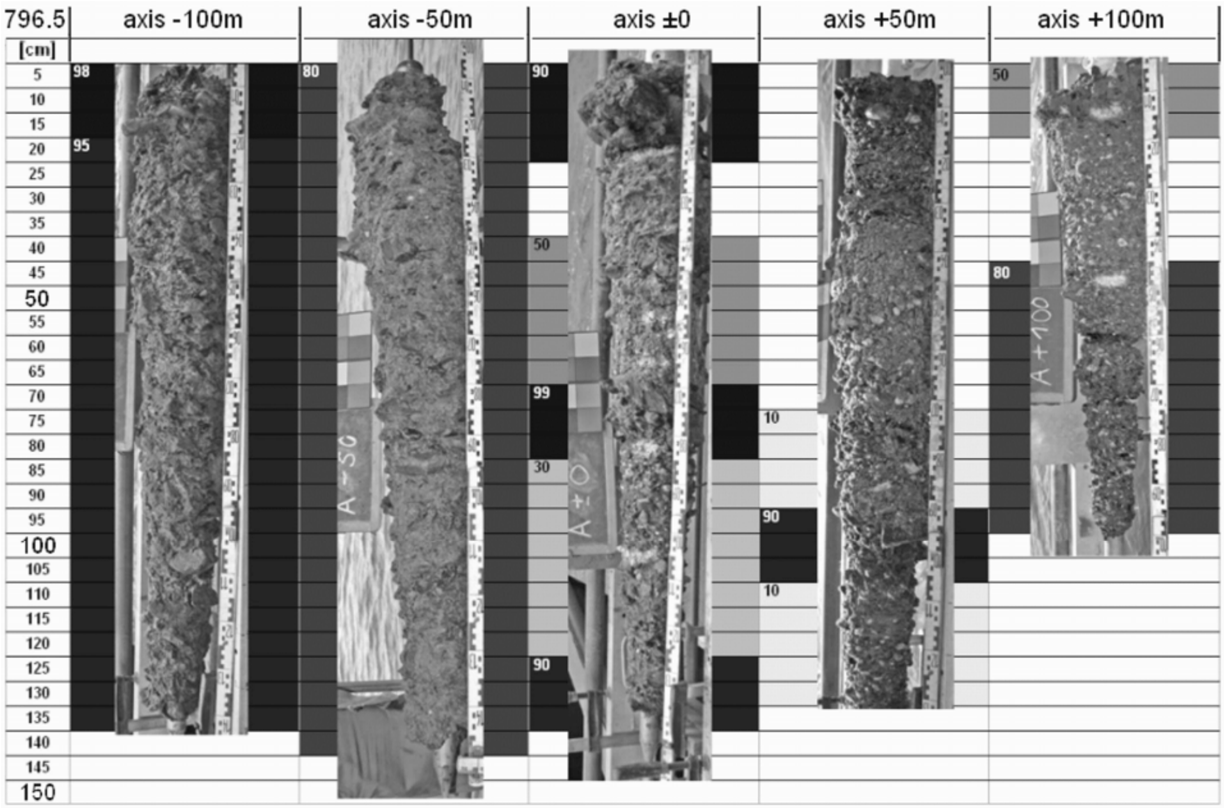


Figure 6. Freeze cores from the field measurements of May 2007, Rhine-km 796.5

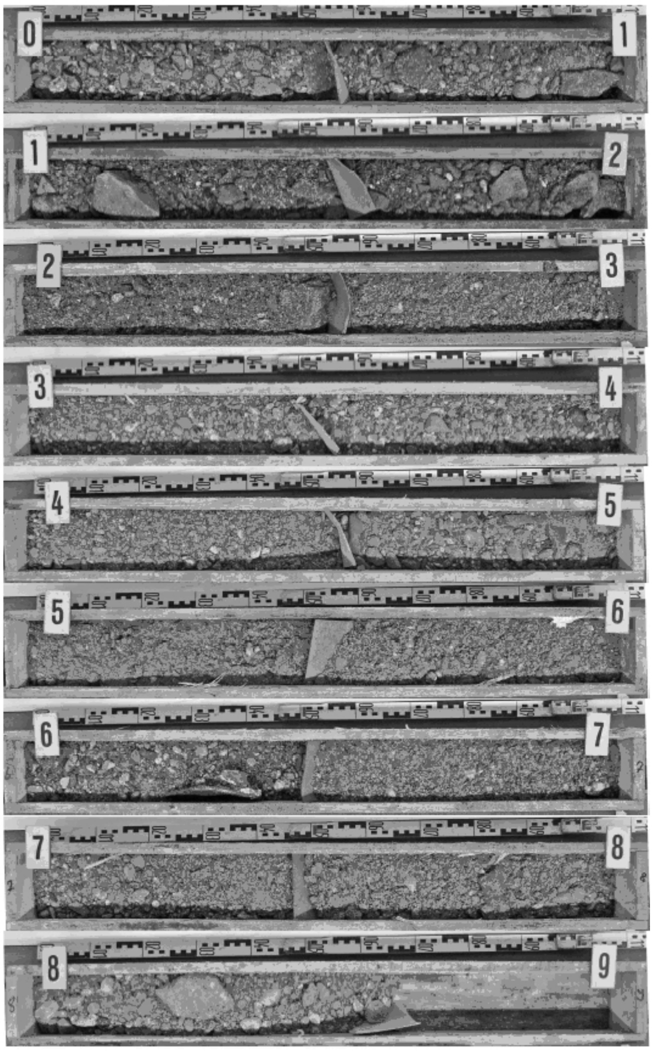


Figure 7. Outcrop samples in 1-m-core boxes, Rhine-km 795.5, axis ± 0

The third campaign was designed to analyse the long-term behaviour of the supplied minestone. A total of 50 drillings of up to 12 m in depth were performed on the stretch of the Rhine River between km 792.0 and km 810.0 during the period between 5th and 29th November 2007 (BAW, 2008b).

The material of the outcrop has been stored in sections of 0.5 m each in 1-m-core boxes (see Figure 7) and could therefore be processed in the modality already described for the freeze cores. The resulting data enable the deeper layers to be taken into account and thus long periods to be considered.

The core and outcrop analysis enables the outstanding questions about the short- and the long-term changes in the particle size distribution and the long-term behaviour of the minestone material to be answered as follows.

The cross-section of the Rhine at km 795.5 provides a typical situation for the core area of mining subsidence and its compensation. It is considered in more detail below to explain the modalities of interpretation. Figure 8 shows the depth extensions and percentages of minestone at the five sample positions by way of a typical example of the manner of dealing with the laboratory evaluations. The information provided by the mine surveyors of the RAG (German Coal Corporation) that the subsidence at Rhine-km 795.5 amounts to about 7 m and extends over almost the entire width of the fairway is reflected in the samples in

Figure 8. The samples can be expected to contain a very high proportion of minestone as the material has been dumped in this area since 1978.

| Axis | -100 | -50 | ±0 | +50 | +100 |
|---|---|---|---|---|---|
| Rhine-km 795.5 | | | | | |
| 0.0 - 0.5 | 90 | 80 | 25 | 5 | 80 |
| 0.5 – 1.0 | 100 | 45 | 65 | 5 | 65 |
| 1.0 – 1.5 | 95 | 70 | 85 | 15 | |
| 1.5 – 2.0 | 100 | 10 | 80 | 70 | 95 |
| 2.0 – 2.3 | 100 | 55 | 25 | 10 | 100 |
| 2.3 – 2.5 | | | | | 100 |
| 2.5 – 3.0 | 100 | 35 | 25 | 10 | 100 |
| 3.0 – 3.5 | 100 | 40 | 5 | 100 | 95 |
| 3.5 – 4.0 | 100 | 45 | 10 | | 100 |
| 4.0 – 4.5 | 100 | 65 | 0 | 40 | 100 |
| 4.5 – 5.0 | 100 | 15 | 0 | 20 | 95 |
| 5.0 – 5.5 | 50 | 25 | 5 | 10 | 10 |
| 5.5 – 6.0 | 25 | 10 | 0 | 5 | 0 |
| 6.0 – 6.2 | 0 | 20 | 5 | 5 | X |
| 6.2 – 6.5 | | 65 | | | |
| 6.5 – 7.0 | 0 | 40 | 10 | 0 | |
| 7.0 – 7.5 | 10 | 0 | 0 | 5 | |
| 7.5 – 8.0 | 0 | 0 | 0 | 0 | |
| 8.0 – 8.5 | 0 | X | 0 | 0 | |

Figure 8. Depth extensions and percentages of minestone in the outcrop samples of Rhine-km 795.5

Table 2. Cross-sectional average percentages and mean extension depth of minestone at the drilling stations

| Stations | Outcrop samples | |
|---|---|---|
| [Rhine-km] | mine stone [%] | extension depth [m] |
| 792.0 | 19 | 0.9 |
| 795.5 | 47 | 6.9 |
| 796.0 | 56 | 5.5 |
| 797.0 | 55 | 9.1 |
| 798.0 | 62 | 3.8 |
| 799.0 | 50 | 2.7 |
| 800.0 | 36 | 1.2 |
| 802.5 | 49 | 2.0 |
| 805.0 | 43 | 0.6 |
| 810.0 | 5 | 0.3 |

The averaging of the minestone distribution first over the depth and then over the lateral extension of the supply area resulted in a percentage of roughly 50 % of minestone for the station at Rhine-km 795.5. Thus, a range of between 5 and 62 percent of the cross-sectional average percentages of minestone for all drilling stations was calculated as summarised in Table 2.

The drilling samples served, inter alia, to define the lower horizon of the minestone. Furthermore, it was then possible to determine the "control volume" required to enable the remaining minestone fraction in the riverbed to be taken into account. The depth and cross-sectional averages of minestone reflect the current condition of the riverbed that has developed as a result of mining subsidence as well as the related compensation policies and their interaction with the seasonally dominated transport regime over several decades.

While Table 2 provides rough indications of the distribution of minestone within the project area, the results of the interpolation or integration of the individual values at the drilling stations provide the balances over the "control volume" of $V_{tot} = 11.5 \cdot 10^6$ m³ for the total volume under consideration and of $V_{act} = 5.5 \cdot 10^6$ m³ for the actually identified quantity of minestone. Assuming a constant bulk density of 1.65 tons/m³ for all materials, a total mass of $m_{tot} = 19.0 \cdot 10^6$ tons and a mass of $m_{act} = 9.1 \cdot 10^6$ tons for the actual proportion of minestone can be calculated.

According to specifications of the WSV the comparable mass of supplied minestone amounts to $m_{tar} = 13.6 \cdot 10^6$ tons. With reference to that quantity the target / actual comparison results in a calculated relative difference of

$$\Delta = \frac{m_{tar} - m_{act}}{m_{tar}} = 0.33 . \qquad (1)$$

It is therefore reasonable to assume that approximately 30 – 35 % of the supplied minestone was removed from the mining area and was thus not available to compensate for subsidence. Due to its high weathering rate the minestone fractions discharged downstream – as documented by numerous bed load measurements and prospecting samples – obviously did not significantly contribute to the preservation of the riverbed of the Lower Rhine River.

## 3 CONCLUSIONS AND RECOMMENDATIONS

Following the closure of the Walsum mine in mid-2008 it was necessary to draw up forecasts of the future stability of the river bed. Stabilisation measures had to be derived for the relevant section of the Lower Rhine River where necessary. The primary objective of the WSV was to design the stretch of the Rhine River affected by subsidence such that the morphological aspects of the river after subsidence and compensation measures gradually adapt to those prevailing in the adjacent river sections (BAW, 2007b).

To this end, the findings of the four investigative stages, i.e.

- chronological study and historical documentation,
- tests on the typical material properties,
- numerical studies in a one-dimensional morphological model and
- several campaigns of field investigations,

were merged and discussed in a concluding synthesis. The following interpretations and constitutive recommendations can be derived from the substantial and final results that have been briefly discussed above.

The findings are broadly consistent. However, they are based on the premise that the weathering behaviour of the minestone during and immediately after dumping was pronounced and that subsequent hydrological occurrences were highly variable. Deeper layers of minestone are exposed during flood events and mix with, and are partly covered by, the highly mobilised natural bed load.

The numerous freeze core samples and exploratory drillings provided clear indications of the interaction and exchange processes that have led to a more or less random arrangement of the supplied minestone. Due to its depth, the remaining minestone in the soil below the mobile layer can indeed be described as “locally stable”, but together with the percentage of minestone in the surface layers only around 65 – 70 % of its total mass can be detected in the riverbed.

However, additional measures are still necessary since approximately 30 – 35 % of the supplied minestone has been eroded and has thus not contributed to compensating for subsidence in the mining area.

If the average depth of the mobile riverbed is estimated at about 0.2 m, and the distance between the cross-sections of Rhine-km 794.0 and 808.0 is taken as its planar extent, the loss of volume of approximately $700 \cdot 10^3$ $m^3$ of minestone has to be compensated for over a width of 250.0 m along the axis of the Rhine River. Both stationary and transient measures are required for the morphological adaptation of the hitherto artificially elevated area in view of the prevailing erosion trends in the relevant stretch of the Rhine River.

A concerted combination of stationary measures such as partial bed stabilisation, coarse particle accumulation, modifications of existing hydraulic structures and measures on the floodplains is proposed. Depending on the needs, the stationary measures can be complemented temporarily and spatially flexibly by artificial bed load supply.

However, further studies in two- or three-dimensional numerical models are required to enable such stationary and temporally variable measures to be planned. The integral part of the morphological after-effects should continue to be investigated in large-scale observations of the existing one-dimensional model of the Lower Rhine River.

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