MILITARY HYDROLOGY

Research & Development Branch

DESTRUCTION AND PROTECTION

OF

DAMS AND LEVEES

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DESTRUCION AND PROTECTION OF DAMS AND LEVEES

During World War II three of Germany's dams located on the MOHNE, SORPE and EDER Rivers were attacked on the same night, This operation was carried out by the Royal Air force during the night of 16 and 17 May, 1943 as a low-level surprise attack from a height of approximately 18 m, using special heavy rotating bombs (Roll Bombs).[1] Figures 1 and 2 show the location of these works. The flood wave released by their destruction caused widespread devastation. To obtain a basis for the preparation of plans for precluding or reducing damages from such occurrences in the future, these flood waves were later carefully studied. It is believed that the results of these investigations are of sufficient general interest to be published.

I. Description of the Dams and the Damages

A. The MOHNE Dam.

This dam was built in the period 1908-1913, from a design by E. LINK, mainly for the purpose of providing domestic and industrial water supply in RUHR area. The drainage area above the dam is 430 km^2, the average annual inflow is $240x10^6$ m^3, the reservoir capacity is $134x10^6$ m^3, and the surface area is 10.2 km^2. This gravity dam with an arched axis is 650 m long at the crest and 40 m high. (Maximum water level 32 m). The top width is 6.25 m and the base width 34 m (Figure 3).

The attack by the Royal Air Force was carried out during the period when the reservoir was completely full. On 17 May 1943 at 12:49 a.m., a bomb exploding close to the face of the dam approximately 10 m below the water surface breached the upper part of the dam. A gap 76 m wide at the top and 22 m deep developed in the center of the dam. Within the next 12 hours $116x10^6$ m^3 of water escaped through this breach. On the 16 of May 1943 the storage in the reservoir was $132.2x10^6$ m^3. It was later determined that the initial rate of flow through the gap was 8,800 m^3/sec. In the narrow MOHNE Valley this caused a surge 10 m high which caused great destruction. This surge was considerably higher than the highest flood of record, the flood of 1890. Approximately 1200 lives were lost. All buildings situated on low ground between the dam and HAGEN (approximately, 65 km downstream) were either swept away or damaged. All bridges for 50 km downstream were destroyed. Eye witnesses report that the water piled up as high as 2 m on the bridges before they collapsed. The power stations, No. I located at the foot of the dam (4,800 kw output, four generating units), and No. II (300 kw, two generating units) located at the re-regulation pool at GUNNE, just disappeared. At the confluence of the RUHR and the RHINE Rivers (148.5 km from the MOHNE Valley dam) the stage rose about 4 m when the crest of the flood wave, 25.5 hours after the catastrophe, passed there. This meant that the discharge of the RHINE River increased by 1100 m^3/sec.

The effects of the rupture of the MOHNE dam were very serious because on one hand this dam was the main source for the water supply of the densely populated RUHR area, and on the other hand its rupture flooded most other water supply plants in the RUHR all the way to ESSEN, and put them out of commission. A large number of towns like HAMME, HAGEN, BOCHUM, and DORTMUND were without water. Also, the pump storage plant at HERDECKE on the RUHR, 60 km below the MOHNE dam, which with its 132,000 kw output is one of the most important power stations of the RHEINISCH-WESTFALISCHEN Electric Power Company (RWE), could not operate for 14 days because its power house was under 2 m of water.

B. The SORPE Dam,

Here we deal with a dam constructed in the period from 1922-1933 as an earth fill structure with a watertight concrete core wall also designed and built under the direction of E. LINK (Figure 3). The height of this dam above the valley floor is 60 m, the maximum water depth is 57 m, and crest is 700 m long. The upstream and downstream slopes at they center of the dam are 1 on 2.25 and 1 on 2.50, respectively. To make it difficult for water to penetrate the dam the upstream part is constructed of impervious material covered by a protective layer. The downstream part is constructed of pervious material to allow that that water which seeps through the impervious part and the core wall to drain as fast as possible. The storage capacity of the SORPE reservoir is $81x10^6$ m^3. When completely full a lake of 3.8 km^2 is created. The annual flow of water from the catchment area into the reservoir is $31x10^6$ m^3.

The air attack on the SORPE dam was carried out at the same hour as the one on the MOHNE dam, apparently with the intent to cause them to fail simultaneously. This earth dam however did not fail, although the crest of the dam received two direct hits which created craters 12 m deep. The attacks on the SORPE dam were later repeated several times, including a concentrated attack on 16 October 1944. In all these attacks 11 hits were scored on this earth dam without causing a collapse or leakage. After the first attack, however, the water level in the reservoir was lowered a few meters as a precautionary measure.

The fact that the gravity masonry dam on the MOHNE was ripped open while the earth dam across the SORPE withstood the attack is of decisive importance. The effect on the RUHR area would have been of catastrophic proportions if the SORPE valley reservoir also would have run out during those early morning hours of the 17 of May 1943, and the two flood waves would have combined and superimposed themselves on each other.

C. The EDER Dam.

This -dam is located at WALDECK in the vicinity of KASSEL and was, after the successful action against the MOHNE dam, the target of the same Royal Air Force outfit. These two dams are only 80 km airline distance apart. The EDER dam is Germany's second largest dam (second only to the BLEILOCK dam on the upper SAALE in THURINGEN), and was constructed in the years 1908-1913 as a rubble masonry gravity structure. This dam stores $202x10^6$ m3 water, and when completely full creates the impressive and beautiful EDER Lake which covers an area of 11.7 km^2. The average annual inflow into the reservoir is $500x10^6$ m^3. The EDER Lake augments low flows, helps control floods on the FULDA and WESER River, benefits navigation, and supplies the MITTELLAND canal with water. In addition, power is generated by the EDER dam. Immediately downstream of the dam are, the power stations HEMFORTH I (13,000 kw)and II (17, 000 kw) with nine generating unit in all. In addition, in HEMFURTH is the pump storage plant WALDECK, which with its four turbines has a peak output of 115,000 kw, and finally there is at AFFOLDERN at the EDER re-regulation pool a small run-of-the-river power plant with a single turbine delivering 2,560 kW.

This arched masonry dam is 400m long at the top, 48 m high and the maximum water depth is 41 m. The wall is about 6 m thick at the crown and 35 m at the base. A cross section is shown in Figure 3.

In the attack on the EDER dam which occurred at 1:20 am on the 17 of May 1943, a hole of about 25 m radius (figures 4 and 5) was blasted through the dam near the left tower (as seen from the downstream side). As the breach was smaller than the one in the MOHNE dam, the time needed for the reservoir to run out was longer than at the MOHNE. The maximum discharge through this breach was computed to have been 8,500 m^3/sec, or to have been of similar magnitude as the flow from the MOHNE dam. The time however to empty the reservoir of 154.4x10^6 m3 out of a total of 202.4XI0^6 m^3 which were in storage at the time of the attack, extended to 36 hours.

Besides the opening which resulted from the blast, cracks and loosened sections appeared in several places. The damage at the power stations at HEMFURTH and AFFOLDER was reported as severe. The flood wave which was able to spread easier in the much larger EDER and FULDA valley, did not have the same catastrophic effect here as it had in the narrow MOHNE and RUHR valley. The damage, however, was still large enough. The river bed of the EDER from the dam to the mouth was completely devastated, and in addition, large land areas were flooded and covered with silt. The retaining dike of the re-regulation pool showed large crevices and washouts. The rapid dropping of the water level in the EDER Lake caused large slides in four places along the shore. The locks of all seven dams on the canalized FULDA between GUNTERHAUSEN and HANNOVERTSCH-MUNDEN were silted in and partly washed out. Manifold damage was caused on the weirs and gates. The flood wave caused a heavy bed load movement which made it necessary to dredge 30,000 m^3 to restore the original conditions on the FULDA. This bed load movement continued in the WESER downstream of HANNOVERISCH-MUNDEN causing shoals which had to be removed by further dredging (app. 5,000 m3). In addition, about 1,000 spur-dikes on the WESER, were either destroyed or damaged. The shore, line, of both the FULDA and WESER heavily damaged. On the WESER alone 5.5 km of shore protection had top be rebuilt.

II. Flow of the MOHNE dam flood wave.

The reconstruction of the movement of the flood wave after the MOHNE dam catastrophe was difficult, due to the destruction or damage of most stream gages on a long reach of river below the dam. Most of_ the gages which were left in operation were incapable of measuring the unusually high stages. For this reason only few definite gage readings are available in the MOHNE and upper RUHR valley. Regular and true measurements were only possible below the town of HAGAN in the middle part of the RUHR valley. However, the marks which the flood left behind made it possible to determine the maximum stages without gage readings. The determination of the time of travel which the flood wave traced was much more difficult. For this it was necessary to rely on the reports of eye witnesses. As it is well known that such reports may be very questionable, a conscientious and critical evaluation of all eye witness reports was performed by the competent authority, Water Resources Control Office (Wasserwirtschaftsamt) at HAGFN. The results of this investigation are presented in table 1 and figures 6 and 7.

A. The flow from the dam.

At the time of the attack the reservoir contained 132.2x10^6 m^3. Regular observations on the reservoir gage were made only after the general agitation and confusion was somewhat reduced at 6 am. The gage readings obtained at the time of attach (12:49 am) and after 6 am are shown in figure 6, and were connected by a curve based on the assumption that the flow had been continuous and that the initial size of the break in the dam was equal to its final size.

This time and the time t and the time difference Δt (columns 1 and 2 of table 1) were determined from the reconstructed curve of the storage volume V_1 as a function of time for points of even $10x10^6$ m^3 volume (column 3 of table 1). A definite amount of water was retained in the HEVE and STOCKUM fore bays, two sub-reservoirs of the MOHNE reservoir, connected with the main basin only by small gates. Column 4 of table 1 takes this into consideration.

The discharge Q = f (t) can be determined either as $Q = \Delta V/\Delta t$ (column 7) or as Q = dv/dt (column 8) the slope of the tangent to the curve V = f (t) at the time t. By this method the maximum discharge Q_{max} = 8,800 m^3/sec was obtained. The discharge however dropped rapidly. At 6 am or 5 hours after the dam break, it was still 2,000 m^3/sec and three hours later 1,000 m^3/sec (figure 6). It can be assumed that by 12 o'clock noon the out flow for practical purposes was complete.

B The flood wave timing in the MOHNE and RUHR valley.

The results determined by the Water Resources Control Office at HAGEN are shown graphically on figure 7. The curves represent the theoretical course of the flood wave. In reality these curves are less regular, because the wave is dependent upon the changing shape of the valley. Where the valley _widens the wave has a chance to spread and its progress is therefore retarded. This was the case especially at the three RUHR lakes. These are the HENGSTEY Lake at HAGEN (1.6 km^2 area and $2.8x10^6$ m^3 storage), the HARKORT Lake (1.4 km^2 area and $3.3x10^6$ m^3 storage), and the BALDENY Lake on the south edge of the city of ESSEN (1.4 km^2 area and $9x10^6$ m^3 storage). The BALDENY Lake was completely empty at the time of the accident in the MOHNE Valley. This lake was emptied as protective measure against air attacks (to make orientation difficult). The HENGSTEY and HARKORT Lakes were full but were immediately emptied when the facts of the catastrophe became known.

To what an extent the BALDENY Lake reduced the approaching flood wave can be seen from the fact that the high water level downstream was lower than the catastrophic flood of 1890, while upstream it was higher. The inflow into BALDENY Lake was about 2, 500 m^3/sec, a flow which theoretically could be held back for one hour. The time of the arrival of the flood wave head that is the beginning of the rise, and the time of the passing of the crest, is shown for the entire reach from the MOHNE Valley to the mouth of the RUHR about 150 km long by curves 1 and 2 of figure 7. The time scale on the left of the figure should be_ used for these two curves only. It is natural that the lag between the beginning of the rise and the passing of the crest increases with increasing distance. At the mouth of the RUHR this lag was 6 hours.

In addition, figure 7 shows the velocity of the wave at its head (curve 3) and at its crest (curve 4). The velocities were determined from curves 1 and 2 according to the equation C = dl/dt which is represented as tangents to these curves. Table 2 shows some of the important values.

C. Stages and Discharges.

In the MOHNE valley the stages exceeded the previously accepted maximum, the flood of 1890, by an average of 3 to 4 m. In the vicinity of HAGEN, about 65 km below the dam, the stage exceeded the, 1890 flood by 2 m, and at the entrance into BALDENY Lake by still 0.50 m. Below the lake the water level approached the 1890 stage within 0.50 m. It was determined that especially high stages occurred wherever the valley became narrow or where bridges and similar structures obstructed the flow.

The measured stages were converted into approximate discharges Q by the use of extrapolated rating curves, in the entire MOHNE and RUHR valley. Curve 5 in figure 7 shows the result. It can be seen that a relatively fast flattening of the flood wave took place. In the approximately 159 km long reach from the origin to the confluence of RUHR and RHEIN, the peak discharge Q changed from 8,800 m^3/sec to 1,840 m^3/sec. Of this amount 740 m^3/sec came from the normal RUHR flow while 1,100 m^3/sec can be charged to the flood. This was determined by gage observations on the RHINE River at DUISBURG just down stream from the mouth of the RUHR.

III. Flow of the EDER Dam flood wave

Figure 8 shows graphically some of the phenomena associated with the failure of the EDER Dam, compiled from investigations made by the Waterways Bureau (WASSERSTRASSENDIREKTION) at HANNOVER. This figure presents basically the same picture as the one representing the failure of the MOHNE dam. It should be noticed that the peak discharge values vary only slightly at both dames (MOHNE Dam Qmax = 8,800 m^3/sec, EDER Dam Qmax = 8,500 m^3/sec). The duration of the outflow, however, is considerably different. While the MOHNE Dam was empty in 12 hours, the 1.4 times as great water volume a the EDER Dam required, thanks to the smaller breach, 48 hours to flow out. Figure 9 represents data on the flow of the flood wave created by the failure of the EDER Dam, in the EDER, FULDA, and WESER valley. The flood wave flattened out rapidly because the water had sufficient space to spread. At 75 km downstream from the dam the stages were below the maximum flood of record (Jan. 1841). At the gage at INTSCHEDE near BREMEN (425.6 km from the dam) the discharge was only 665 m^3/sec, and about 58x106 m^3, that is, 1/3 of the amount that escaped from the reservoir was held by the valley storage of the floodplain above this point.

The velocity of the flood wave too was less here than in the MOHNE valley

These computed values were verified in August 1964 when a flood wave, intentionally released from the rebuilt EDER Dam, was observed throughout its travel. The mean velocities determined in this test for the reach from the dam to HANNOVERISOH-MUNDEN, a distance of 94.4 km, were 2.00 m/sec for the head and 1.31 m/sec for the crest of the flood wave. These values are sufficiently close to the values shown in table 3.

One of the most urgent, simplest and cheapest safety measures that can be devised against the effects of dam failures is a careful study of the travel of intentionally released flood waves. This would not only yield information regarding the speed of events during an actual dam failure, but would also point out points of probable danger in time to develop a safety plan and carry out protective measures.

IV. Air Attacks on Canals.

Following the summer of 1944, navigation and power canals became the.- targets of air-attacks. Especially those stretches of canals were bombed where it was either possible to cause flooding, due to the fact that the canal level was higher than the surrounding terrain, or where structures like bridges, locks, or canal intersection, whose reconstruction is difficult or time consuming, could be damaged or destroyed. An especially worth-while target was the vicinity of DATTELN (figure 1) where several canals join.

A. The DORTMUND-EMS Canal.

This canal is one of the most important waterways in Germany. It connects_ the RUHR area with the North Sea, has a depth of 3.20 m and an average width at the water level of 40m. The channel sides slope in the upper part 1 on 2.5, in the lower 1 on 4. The bottom is 20 m wide and slightly sloped at 1 on 40. Where the canal runs above the surrounding terrain, the dikes have a top width of 3.50 m and a landside slope of 1 on 1.5. This canal was attacked 6 times in the vicinity of DATTELN from 23 September 1944 to the end of the war. The damages were so extensive that only in March 1946 navigation was provisionally reestablished. The first attack caused a dike failure through which a 30 km long reach with a water content of $3x10^6$ x m^3 ran dry.

B. The WESEL DATTEIN Canal.

The dikes along this canal have a top width of 8.00 m, landside slopes of 1 on 3 and waterside slopes of l on 3 or 1 on 4. The water depth is 4.20 m. This dike was damaged by bombs in one place so badly that $2.5x10^6$ m^3 of water poured out washing 30,000 m^3 of soil away.

C. The DATTELN-HAM Canal.

This waterway was hit by more than 100 bombs in a place where the dike crests rise 6 to 7 m above the surrounding terrain. The top width of the dike is 3.50 m and the water and land side slopes are 1 on 3 and 1 on 2 respectively. By this bombing the water was released and 20,000 m^3 of soil were washed away.

The high dividing levee between the canal and the river LIPPE, a levee with a top width of 5 to 8 m and slopes towards the river of 1 on 2, also received more than 100 hits. However, it did not collapse and withstood a flood on the LIPPE River without failure in spite of the many weakened places.

D. The RHEIN-HERNE Canal.

In this case we were successful to close each breach opened by the fall of heavy bombs. Dike failures which would have emptied the canal did not occur.

E. The Canal "MITTLERE ISAR.

This 53.5 km long canal, corned by the power company "BAYERNWERK AG" branches from the ISAR river at the northeast edge of the City of MUNCHEN (figure 11), and carrying at the intake a maximum flow of 125 m^3/sec, supplies four power stations FINSING, AUGKIRCHEN, EITTING AND PFROMBACH with a combined output of 82,500 kw. Air attacks were carried out against the upper reach on the 9 of June and the 11 and 13 of July 1944. A chart showing the bomb hits was drawn by the construction office of the “BAYERNWERK AG” and is shown on figure 13. The canal did not leak out in spite of 60 to 70 hits. The levee fill consisting of gravel and clay closed its own breaches by slumping. Even the power station continued to operate on a reduced scale (1/4 to 1/3 of normal output). Figure 10 shows a damaged section of the ISAR canal where the concrete lining of the slopes can still be seen. The repair work took one-half year.

The experience gained from air attacks on canals has taught us that the usual dike top width of 3.5 m is too small. However, the example of the MITTLERE-ISAR canal shows that in spite of this, the dike failure is not inevitable. It is recommended that the crests be enlarged to about 6 m thickness. The failure of the levee on the WESEL-DATTELN canal, in spite of its crest thickness of 8 m, proves that a thickness of 6 m can still be insufficient. It is most likely impossible, for economic reasons, to increase the top width of the dikes above 6 m.

Complete safety is not obtained, but for most instances, the safety is sufficient, especially if the fill material is properly selected. It would be asking too much to require a levee cross section which would preclude all dangers. If such an idea is carried through, one soon reaches dimensions which can not be technically or economically justified.

V. MODEL TESTS

During studies made in 1935 by the Saxonian Waterways Construction Bureau in DRESDEN regarding a storage basin near PIRNA (figure 14), the question as to the extent of damages which would be caused by a destruction of the earth dam of the basin, was raised. This basin was to be built for the purpose of facilitating navigation on the ELBE during low flows, and was to have a content of 120×10^6 m^3. An answer was required especially regarding the effect of a flood wave on the City of DRESDEN, located only 17 km from the basin, in case of a dam failure. As there was no experience to draw from, the author of this paper was commissioned to find the answer to these questions by model tests. The tests showed that a flood wave originating at the PIRNA basin would flatten out comparatively fast because sufficient space exists between PIRNA and DRESDEN for over bank flow. This result was confirmed by the phenomenas observed at the failures of the MOHNE and the EDER dams. A sufficiently good quantitative similarity was also found. (3) The model tests showed further that the stages in the City of DRESDEN during the passage of such a flood wave would not be appreciably higher than the stages during the catastrophic flood of 1845, and the old bridges with their comparatively small openings (figure 15) were just large enough to pass such a flood. The effects of damage of the dam crest are more serious. The model tests showed that an earth dam is beyond all help if water from the basin, following as penetrating damage can leak out, even if it is in the beginning only a thin and intermittent jet. The water then begins to scour and gnaws a comparatively narrow, steadily increasing in depth, slat in the dam. This process does not stop until the entire reservoir is empty. The different phases of such a dam failure in the model are shown on figures 16 A through G. To make the model conditions as similar as possible to nature, blasts of one or more 200 gram charges (mostly TNT) were set off on a dam model 3 m high and 2 m wide at the top, which was erected in the open. The fill material was nonbinding sands with from 0.02 to 2 millimeter grain size. The proportionality law of explosions is given by the formula $t = aVL$ or $t^3 = a^3L$, in which t is the depth of the crater in meters and L is the amount of explosives in kilograms. This shows that eight times as much explosive is necessary to double the depth of the crater. The factor "a" is dependent on the soil condition and in this case was found to be 0.73. It was also determined that "a" is little dependent on the type of explosive used. It was assumed in all tests that the explosive occurred at optimum depth (about 0.8t) and that a crater with the natural slope of 36^0 (or an overall angle of 108°) was found. The proportionality law of explosions was checked and confirmed for charges up to 1,000 kg. The values for light sandy soils are given in table 4 (status 1945).

All model tests, regardless of their scale, showed conclusively that any leakage, even an insignificant one, represents primary danger because it leads without fail to a dam break, except if it is possible to stop the flaw at the damage point immediately.

This points the way towards the development of earth dams of such form and size that would make the probability of or damage causing a leak a small one. This means thicker dams than before, especially at the top, and flatter slopes. For the earth dam of the proposed PIRNA reservoir, which was to be about 30 m high, the crest width was changed from 10 to 30 m, and the slope from 1 on 4 to 1 on 2.5, as a result of these model tests. However, this design has not been executed. These dimensions appear unreasonable. However, they are not if you compare them with the Russian earth dams on the WOLGA. The dam at UGLITSCH is at the normal water surface elevation 60 m thick, and the earth dam near RYBINSK is even 147 m thick. It must be remembered that there are in the "RYBINSK SEA" nearly $25x10^9$ m^3 of water which in a dam failure would cause an immense flood.

With the crater shape and the scale relation determined by the model tests, all further work can be done graphically. Figure 17 shows this as applied to the dam at PIRNA under the assumption that 11 and 9-1,000 kg charges respectively were simultaneously exploded at optimum depth in the dam crest. In the first case (a) the dam would be cut through completely while in the -second case (b) several humps would remain which the meter surge created by the explosion would scour away. The model tests confirmed that the assumption was correct. It is assumed that all charges are simultaneously detonated. If this is not the case, the effect will be considerably reduced, because the late blasts would partially fill in the craters blown by the early ones. This is the reason why the earth dam across the SORPE River withstood 11 heavy bomb blasts. The case a the MITTLERE ISAR canal shows that a bomb mosaic must not necessarily cause a dam failure.

VI. Discussion and Conclusion

The catastrophes which occurred in the MOHNE and EDER valleys during the late war, and the failures of the levees along several canals, point up the fact that in the planning of hydraulic structures protection against intentional destruction needs more study today than ever before. Complete and absolute protection is impossible especially because in the progress of engineering the meaning of safety is a continuously changing one. However, as most hydraulic structures, especially dams, are long-term projects which fulfill their purpose for a generation or more protection is very difficult because it is impossible to foresee the development of engineering for Centuries ahead. It is the duty of every responsible engineer to plan ahead safety measures, and continue to improve them which protect against foreseeable dangers and are possible, sensible and economical.

In the case of dams and levees the following conclusions were reached:

1. Earth dams provide greater protection against intentional destruction than do masonry dams. Whenever it is possible to erect an earth dam in place of a masonry one, this possibility should be explored. Buttress dams are especially vulnerable.

2. In an emergency it is usually sufficient to lower the water level a few meters to give a fair degree of protection to both earth and masonry dams.

3. It appears that in the future, larger cross sections than are normal today, at least, near the top, will be necessary on both earth and masonry dams. To the considerations of design used up to now, such as statics and economy, a new one, protection against willful destruction, must be added.

4. The most important step in protecting earth dams is leak proofing. Once water has found its way to the downstream or land side of a dam, an embankment failure cannot be averted. The process of destruction once begun, continues automatically. Relief is possible only in the earliest phases.

5. Flood waves created by dam failures may have catastrophic effects in narrow valleys and near flow obstructions. In wider valleys where the water can spread, the crest of the flood wave flattens out rapidly and soon loses its destructive force. In the RUHR areas artificial lakes helped to reduce the flood created by the failure of the MOHNE dam. Storage basins like these will prove themselves helpful in many instances.

6. Safety can be improved by releasing trial flood waves from dams, to discover hidden danger sources in advance and to institute timely, correct protection measures.

7. Model tests have shown themselves as valuable, maybe even an indispensable aid in the design of earth dams and levees in connection with their safety against intentional destruction. It also is believed that model tests would help to judge the safety of masonry structures against such destruction.

Footnotes:

1. See also "Grundsatzliches zur Wahl des Staumauertyps fur grosse Staubecken" SBZ 1948, Nr. 11, page 150,

2. The warning system operated excellently during the failure of the MOHNE dam. Villages and towns in the MOHNE and RUHR valley were informed of accident in the shortest possible time. The many fatalities, especially in the town of NEHEIM, occurred because the population did not grasp the seriousness of the catastrophe.

3. The main difficulty in reproducing a flood flow in a model is the reproduction of the roughness in the flood plain. This is only possible when sufficient and accurate data are available regarding the natural conditions.

TITLES AND GLOSSARY OF TABIES AND FIGURES

<u>Tabelle 1</u>	Table 1
UHRZEIT am 17. Mai 1943	Time on the 17th May 1943.
Aeitdifferenz in Sekunderi	Time interval in seconds.
Inhalt des Staubeckens in Mio 0	Content of reservoir in millions cubic meters.
Differenz in Mio m^3	Change in millions cubic meters.
Ausgeflossenes Wasservolumen in Mio m3	Water volume discharged in millions cubic meters.
Sekundlich ausgeflossene Wassermenge in m3/sece	Discharge in cubic meters per second.

<u>Tabelle 2.</u> (Table 2) Velocity of the wave head and crest in the MOHNE and RUHR Valley in meters per second.

Stelle	Location
Sperre	Dam
Mundung in den Rhein	Confluence with RHEIN
Durchsch¢nit tswert	Average value
Wallenkopf	Wave head
Wellenscheitel	Wave crest

<u>Tabelle 3.</u> (Table 3) Velocity of the wave head and crest from the EDER dam in meters per second.

Stelle)
Sperre)
Wellenkopf) See glossary for table 2
Wellenscheitel)

bei Bremen

<u>Tabelle 4</u>, (Table 4) Blast effects in light sandy soil.

Sprengladung	Explosive charge

Tri chter	Crater
Tiefe	Depth
Modellversuch	Model test

Bild 1. (Figure 1) Location map of MOHNE and SORPE dam and the navigation canals in the RUHR area. Scale 1:800,000

Talsperre	Dam
Kanal	Canal
See	Lake

Bild 2. (Figure;-2), Over--all map of the EDER-FULDA-WESER Rivers and MITTELLAND canal drainage area. Scale 1:3,000,000

Bild 3. (Figure 3) Cross-sections through the MOHNE, SORPE and EDER dam. Scale 1:3000

Talsperre	Dam
Schutzschichte	Protective layer
Mittel	Mean
Schuttung aus dichtem material	Fill of impervious material
Beton-Dichtungskern	Concrete core
Schuttung aus material mit stark En Gehalt an Kies, Geroll and steinbruchabfall gewalzt.	Fill material containing much gravel, rubble and quarry spoils, rolled.

Bild. 4 , (Figure 4) Breach in the EDER dam.

Bild 5. (Figure 5) EDER dam after destruction. Upstream face

Bild 6. (Figure 6) Flow from the MOHNE dam reservoir.

Volumen	Volume
Uhrzeit	time
Secarndliche W?hssermenge	Discharge
Sekundliche Abflussmenge	Discharge
Zeitpunkt des bru ches der sperre	Time of the dam failure
Inhalt des Staubeckens	Content of the Reservoir
Gesamtes ausgeflossenes Wasservolumen	Total water volume discharged

Beobachtungen am Pegal des Stausees	Observations on the reservoir gage

Bild 7. (Figure 7) Flood wave at the breach of the MOHNE dam; timing, velocity and discharges.

Uhrzeit T (Stunden)	Time t (hours)
Entfernumg L van der MOHNE-Talspeere in km	Distance L from MOHNE dam in kilometers
Sekundliche Abfussmenge Q m^3/s in MOHNE-u Ruhrtal	Discharge Q cubic meters per second in the MOHNE and RUHR valley
Schnelligkeit C in m/s	Velocity C in meters per second
Beobachtete Werte fur die Kurven 1 u 2	Observed values for curves 1 and 2
Beginn des Steigens (Wellenkopf)	Begin of rise (wave head
Wellenscheitel	Wave crest
Bruch der Staumoner	Failure of masonry dam
Schnelligkeit des Wellenkopfes	Velocity of the crest
Secondliche Abflussmenge	Discharge
Schnelligkeit des Wellenscheital	Velocity of the crest
Pagel	Gage
P.	Gage
Schleuse	Gate

Bild 8. (Figure 8) Flow from the EDER Valley reservoir

(See glossary to figure 6)

Bild 9. (Figure 9) Floodwave in the EDER, FiJEDA and WESER rivers due to the break of the EDER dam.

Gesamte Abflussmenge beim Bruch der Speere	Total volume discharged by the dam failure
Hochstes bekanntes Hockwasser vom Jan 1841	Highest known flood, Jan. 1841
Hoch rasserwelle mach den Bruch der EDER talspere	Flood wave following the failure of the EDER dam

Bild 10. (Figure 10) Damages to the MITTLERE ISAR canal,

Bild 11. (Figure 11) Situation plan of the ISAR canal; 1:750,000

Wehr	Weir
Kanal	Canal
K.W.	Power Station
Ausgleich-Weiher	Re-regulation pool

Bild 12_0 ,j'igx=e12) Cross section through the levee in the area shown in figure 13.

Betonschale als Cichtung von Boschung	Concrete liner for waterproofing of slopes and invert, average 20 centi-meter thick.

Bild 13. (Figure 13) Bomb hit diagram from the air attacks on the MITTLERE ISAR canal below MUNCHEN, Plan 1:17,500

Wehr and Einlaufbauwerk	Weir and intake structure
Brucke	Bridge

Bild 14. (Figure 14) Situation plan of the proposed reservoir at PIRNA above DRESDEN

Oberfloche	Surface area
Inhalt	Content

Bud 15. (Figure 15) Model for the flood flow tests from PIMA reservoir.

Bild 16. (Figure 16) a through g. Model test of an earth dam failure. Height of the model dam 3 m. top vddth 2 m.

Bild 17. (Figure 17) Dike for PIRNA with different blast oraters. Cross-section . Scale 1:1200.

Elf	Eleven
Neun	Nine
Ladungen	Charges
Trichter	Crater
Durchmesser	Diameter

NOTE: An geographic and other names are shown in capital letters. The German spelling is used so that they match the maps presented.

TABLE 1 – (MOHNE DAM FLOODWAVE DATA)

Time on 17 May 1943	Time Interval (Sec)	Volume of Reservoir (mill.m³)		Change in Volume (mill.m³)	Total Volume Discharged (mill.m³)	Discharge in cubic meters per second	
t	t	V_1	V_2	V	V	Q	Q
1	2	3	4	5	6	7	8
0:49		132.2	132.2		0		8800
	1380			11.76		8520	
1:12		120	120.44		11.76		8060
	1080			8.42		7800	
1:30		110	112.02		20.18		7040
	1320			8.55		6480	
1:52		100	103.47		28.73		6480
	1440			8.52		5920	
2:16		90	94.95		37.25		5560
	1680			9.50		5660	
2:44		80	85.45		46.75		5040
	2040			9.47		4640	
3:18		70	75.98		56.22		4350
	2460			9.69		3940	
3:59		60	66.29		65.91		3600
	3180			10.00		3140	
4:52		50	56.29		75.91		2780
	4020			10.00		2490	
5:59		40	46.29		85.91		1990
	6000			10.00		1670	
7:39		30	36.29		95.91		1530
	12300			10.00		813	
11:04		20	26.29		105.91		556

TABLE 2 - VELOCITY OF THE WAVE HEAD AND CREST IN THE MOHNE AND RUHR VALLEY

Location	Dam (m/sec)	Confluence with RHEIN (m/sec)	Average value (m/sec)
Wave Head	7.36	1.445	2.88
Wave Crest	4.15	1.195	1.89

TABLE 3 - VELOCITY OF THE WAVE HEAD AND CREST FROM THE EDER DAM

Location	Dam (m/sec)	Bremen (m/sec)
Wave Head	2.39	1.22
Wave Crest	1.28	1.08

TABLE 4 - BLAST EFFECTS IN LIGHT SANDY SOIL

Explosive charge (kg)	0.2*	100	250	500	1000
Crater Depth (m)	0.43	3.4	4.6	5.8	7.3
Crater Max. Diameter (m)	1.2	9.4	12.7	16.0	20.0

*Model Test

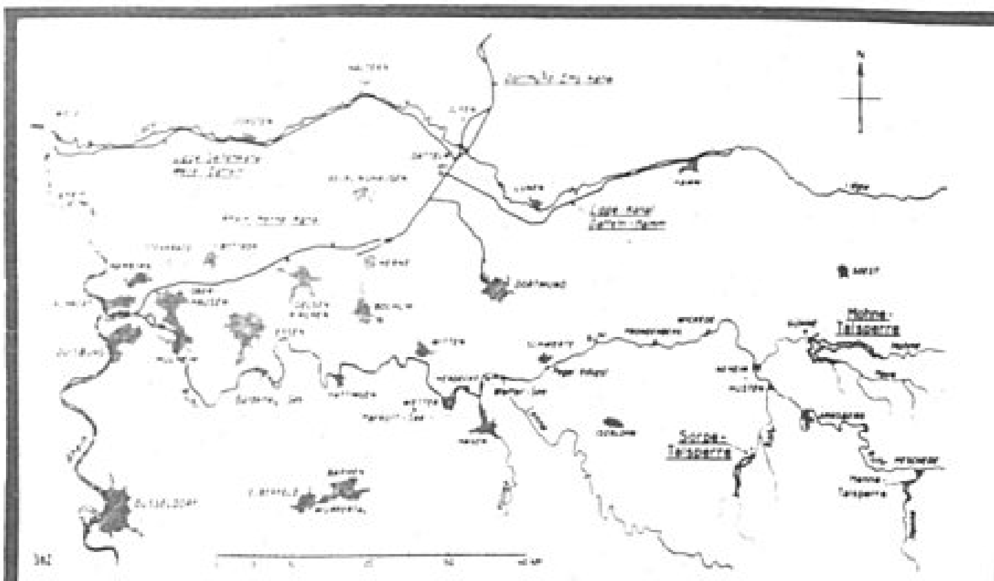


Figure 1 Location map of MOHNE and SORPE dam and navigation canals in the RUHR area

Figure 2 Over-all map of the EDER-FULDA-WESER Rivers and MITTELAND canal drainage area.

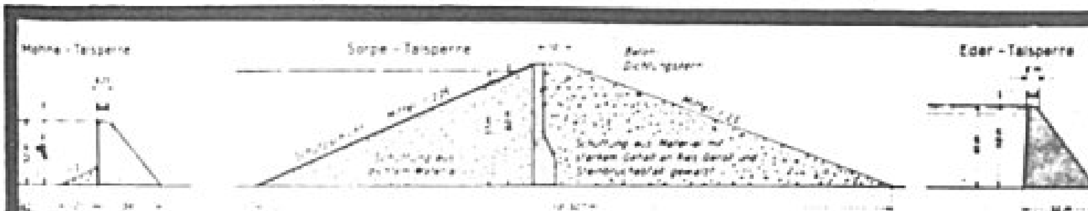


Figure 3 Cross-sections through the MOHNE, SORPE and EDER dam. Scale 1:3000

Figure 4   Breach in the EDER dam.

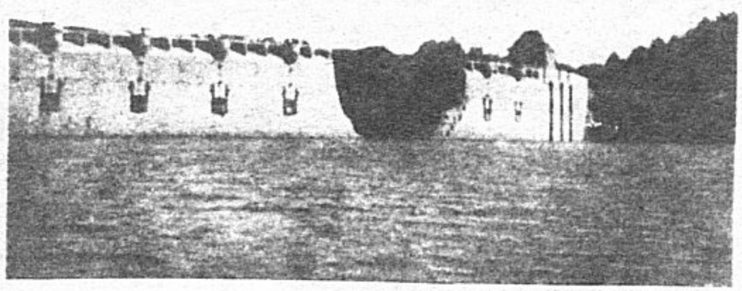


Figure 5   EDER dam after destruction. Upstream face.

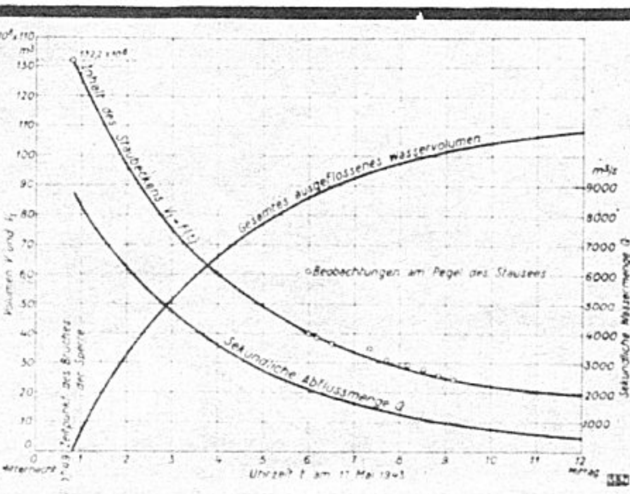


Figure 6   Flow from the MOHNE dam reservoir.

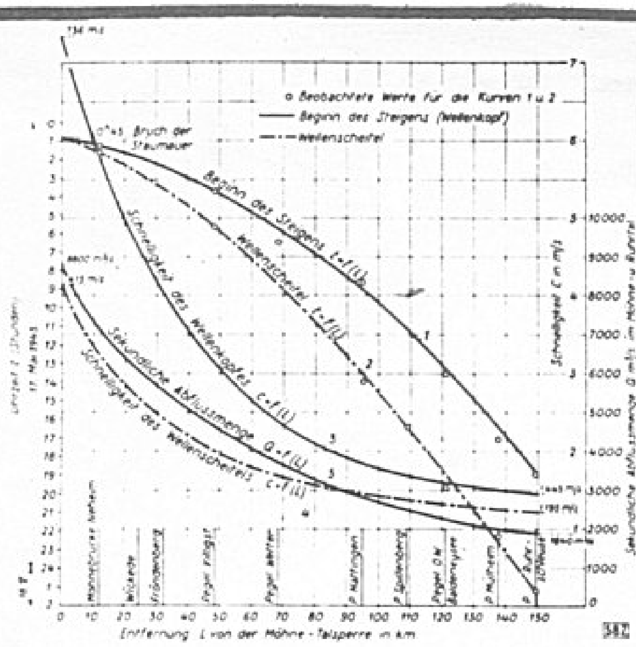


Figure 7 Floodwave at the breach of MOHNE dam; velocity and discharge.

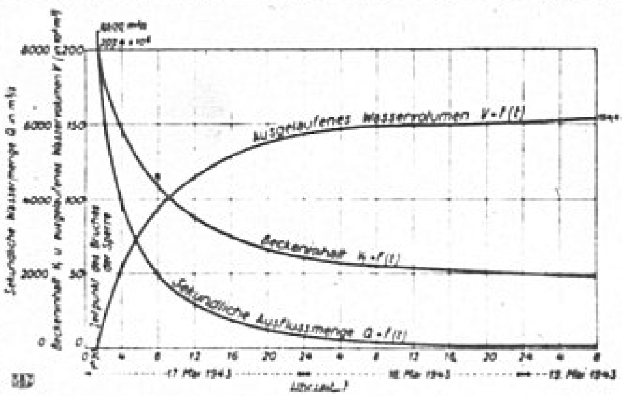


Figure 8 Flow from the EDER Valley reservoir.

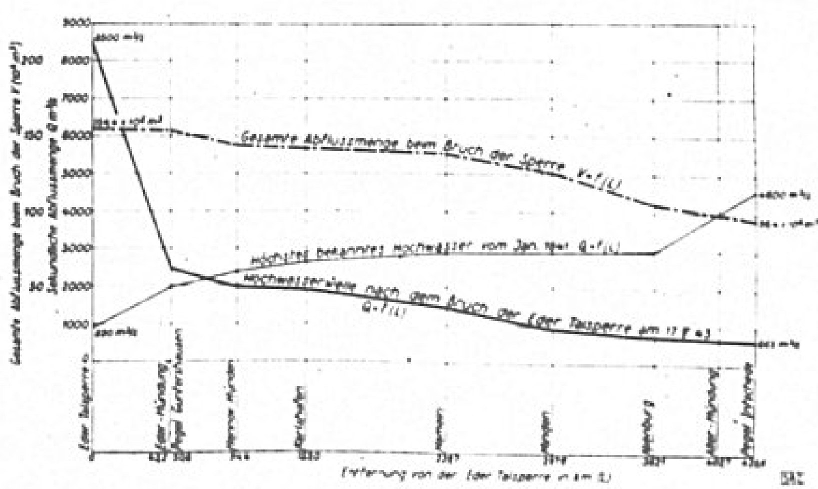


Figure 9 Floodwave in the EDER, FULDA and WESER Rivers due to the break of the EDER dam.

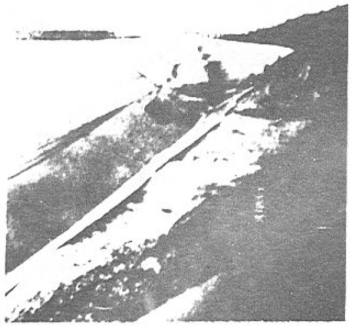


Figure 10 Damages to the MITTLERE ISAR canal.

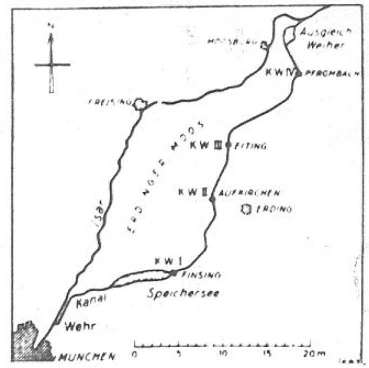


Figure 11 Situation plan of the ISAR canal.

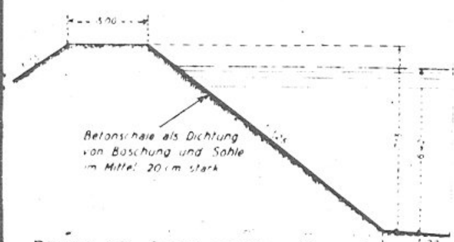


Figure 12 Cross-section through the levee in the area shown in figure 13.

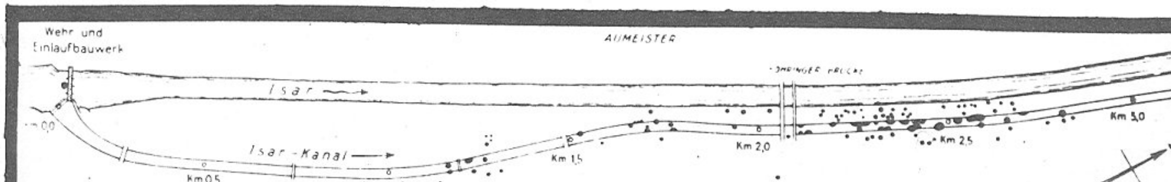
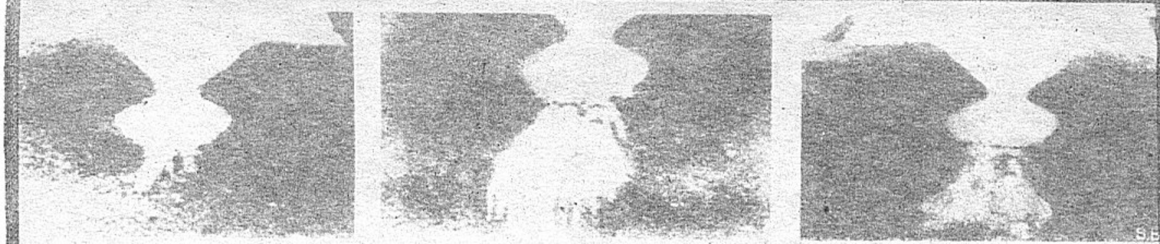
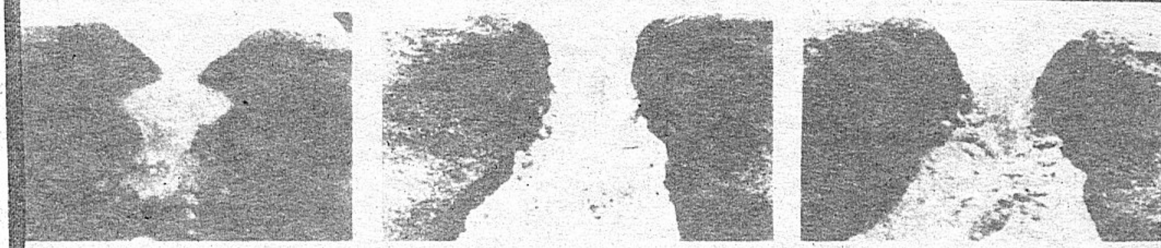


Figure 13 Bomb hit diagram from the air attacks on the MITTLERE ISAR canal below MUNCHEN. Plan 1:17,500

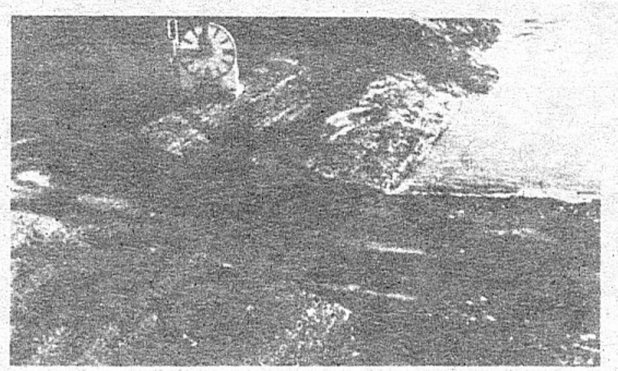


16 a

Figure 16 A through g. Model test of an earth dam failure. Height of model dam 3 m. top, width 2m



16 d 16 e 16 f



16 g

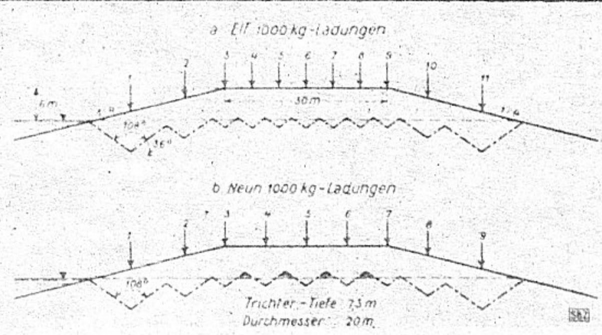


Figure 17 Dike for PIRNA with different blast craters. Cross-section.