GLACIER LAKE OUTBURST FLOOD (GLOF) MITIGATION PROJECT, LUNANA, BHUTAN

Technical Mitigation Measures Thorthormi Outlet

by

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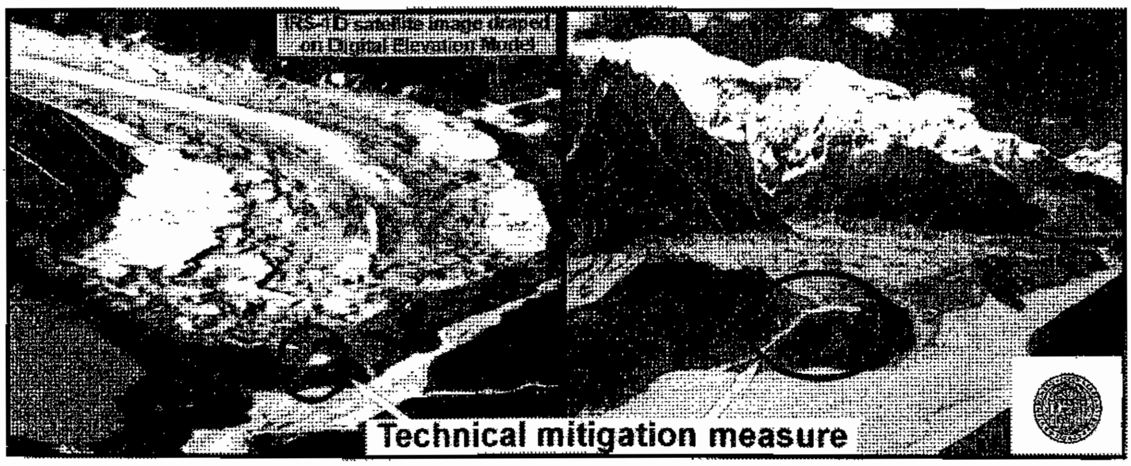

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CONTENT

1 ABSTRACT

During the last four years a detailed GLOF hazard assessment was carried out in the upper watershed of the Pho river, namely in the Lunana and the Tarina area (see reports HÄUSLER et al., 2000; LEBER et al., 2001, 2002, 2003). Based on satellite image interpretation and field investigation different scenarios of possible GLOFs – occurring under worst-case conditions in the future - were elaborated by the Austro-Bhutanese team.

Amongst these scenarios the **"Thorthormi GLOF scenario"**, which is to be **expected to happen in the near future (<10 years) under worst-case conditions**, is the most severe one.

Near the **terminus of the large Thorthormi glacier a net of several supraglacial lakes** is developed. Due to fast glacier melting in the Lunana area these supraglacial lakes are extending – and it is **expected that within 10 years a larger proglacial lake will form**. In that case it is **likely** that the at present already destabilized damming moraine will give way – leading to a **glacier lake outburst flood (GLOF)** devastating the downstream valley.

To avoid this development the **execution of technical mitigation measures** was **proposed by the Austrian team** to the Department of Geology and Mines. Within the next years the **outlet of the Thorthormi lake should be widened and deepened to lower the water table of the existing lakes and to guarantee a free discharge of the runoff of the glacier system**.

The planning of **the technical mitigation measures presented in this report is based on information gained during the previous project phases**. Due to the fact that **there never was the intention behind the previous work** and especially during data collection and measurement **to provide very detailed information required for the planning and execution of a technical project** – it is evident that this data can only serve as a rough basis for the design of the widening of the Thorthormi outlet cannel. Given the extreme urgency – expressed by the Department of Geology and Mines, Royal Government of Bhutan – making a longer planning phase including field survey impossible, the Austrian expert group agreed to "take what is available". Due to these **constraints** the **present report on proposed measures** presented by the Austrian expert group **can only serve as a rough guideline – the final responsibility for the execution of the technical mitigation measures rests with the Department of Geology and Mines, Royal Government of Bhutan.**

As a feasible GLOF mitigation measure the lowering of the actual water level in the supraglacial lakes by **excavating a trench through the moraine crest at the active spillway channel** and the **lowering and widening of the upper part of the channel** is proposed. To limit the construction time and to avoid very rough working conditions the "wet work" (i.e. below the channel water line) must be reduced. This is achieved by the construction of a coffer dam at the channel inlet for each down-cutting step and by draining of the **design discharge of 4 m³/sec** through an **artificial pipe system (2 PE pipes with a diameter of 0.8 m) to be inserted** in the channel.

It is proposed to execute the **necessary excavation work in 4 down cutting phases - like outlined in the attached maps- until the lake water level has been lowered by 5 m**. Each of these phases consists of the **following steps**:

- Establishment of a water diversion by the construction of a coffer dam with pipe conduits.
- Establishment of stable sideslopes on both sides of the channel.
- Widening of the channel bed.
- Lowering of the channel bed.
- Opening of the coffer dam (not at pipe location) and shift of the coffer dam to the new lake water shoreline.

After the base level of the trench is established the armouring layer build up by larger boulders can be executed, starting at the lower end with the foundation. Also for this procedure a water diversion is recommended.

During the down cutting a **stable trench has to be guaranteed** following the conditions specified in this report (e.g. channel bed slope of 1:20, maximum sideslope of 2:3).

Based on the length of the trench to be excavated and its cross section area the **total excavation volume was calculated to be approx. 34500 m³.** The **smaller grain sizes** (<20 mm) of the excavated material can be **used for the construction of the coffer dam, larger grain sizes** (boulder >0.5 m diameter) can be used for the construction of the **channel armouring layer**. Due to the fact that the **quantity of material showing smaller grain sizes** – like necessary for the construction of the coffer dam is **not sufficient - additional 8000 m³** have to be **excavated**.

To complete the **total work load** in total **83500 man days** are necessary. Assuming the **deployment of 300 workers** (20 parties with 14 workers and one supervisor) **the technical mitigation can be completed within four working seasons**.

The preliminary calculation of the cost for the mitigation works at the Thorthormi shows that to cover the cost for the first phase approx. 39 million (NU 38.942.400) Ngultrum are required (what approx. equals 739.000 EURO). The other three phases require approx. 27.6 million (NU 27.558.240) Ngultrum each year (what equals approx. 522.971 EURO).

The **total cost to finish the technical mitigation measures** at the Thorthormi lake is **assumed to be 121.6 million Ngultrum, what equals approx. 2.3 million EURO.**

2 BACKGROUND INFORMATION ABOUT PREVIOUS WORK IN THE THORTHORMI AREA

In 1994 a Glacier Lake Outburst Flood (GLOF) originating at the Luggye Lake, Lunana area, Gasa province devastated the downstream area along the Pho Chhu, killing 21 people, damaging Punakha Dzong, houses, infrastructure and arable land (WATANABE & ROTHACHER, 1996). This disastrous event raised the awareness of the local politicians, concerned authorities and of the population for the risk of glacial hazards in the High Himalayan watersheds. Different expeditions were sent by the Department of Geology and Mines to Lunana to assess the future risk of GLOF hazards (TSHERING TASHI et al., 1994). The Raphstreng glacier lake, close to the Thorthormi glacier, was found ready to burst – immediate technical mitigation measures (widening of the outlet thereby lowering the water table of the lake) were started by a Bhutanese-Indian team (GEOLOGICAL SURVEY OF INDIA; 1995; WAPCOS, 1997). Due to the fact that there exists an interconnected system of different glaciers and glacial lakes in the Lunana area (see Figure 2.1) – with different hazard processes and triggering mechanisms – an Austrian expert group was called in for assistance in 1998. Based on a detailed hazard assessment procedure combining the interpretation of remote sensing data with field mapping and computer simulations, hazard scenarios were defined for the Lunana area and the upper reaches of the Pho Chhu watershed and technical and non-technical mitigation measures were proposed to the Royal Government of Bhutan (BRAUNER et al., 2003; HÄUSLER et al., 2000; LEBER et al., 2002, 2003).

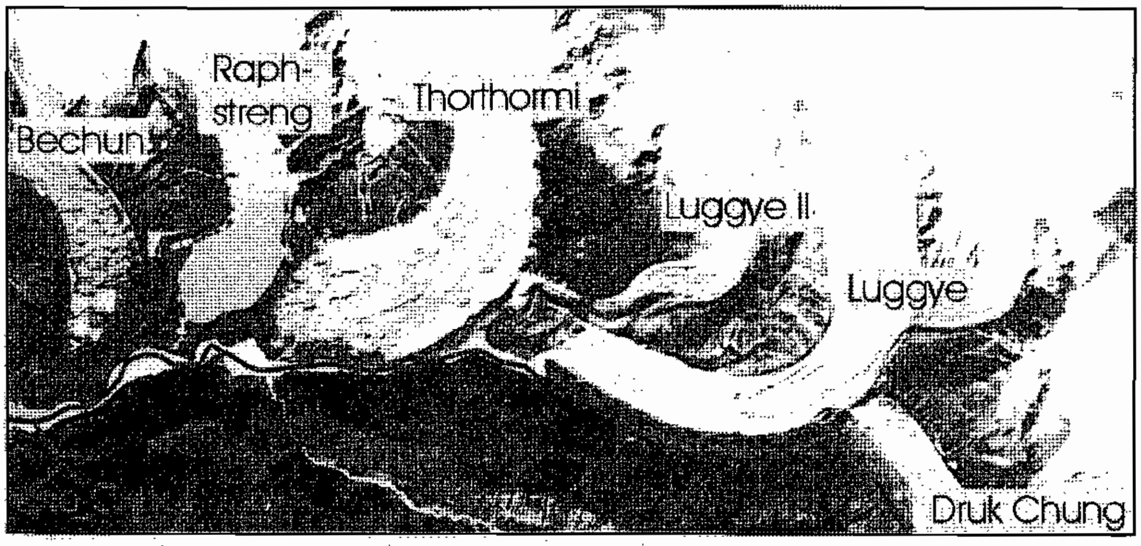

Figure 2.1: Interconnected system of glaciers and glacier lakes in the Lunana area, upper Pho Chhu watershed.

The Thorthormi area itself was investigated in detail in summer 1999 using an interdisciplinary approach combining different field methods (geomorphological and geological mapping, engineering geodetic survey, engineering geophysics, hydrogeology) to assess the risk of future glacier hazards. The location was revisited by the Austro-Bhutanese team in summer 2000 and 2003 to document changes (e.g. expansion of glacier lakes due to excessive melting of glaciers). A final evaluation of all available information led to the definition of hazard scenarios with a considerable downstream impact and to the definition of recommended mitigation measures (LEBER et al., 2002).

2.1 GLOF hazard scenario "Thorthormi glacier/lakes"

According to the **hazard assessment methodology defined by the Austro-Bhutanese team** for the upper watershed of the Pho river, combining remote sensing methods, field mapping, computer calculations and simulations for every glacier/glacier lake area, the geo-hazard potential was evaluated (see Table 4.9.1 in LEBER et al., 2002). The geo-hazard risk evaluation matrix for the Thorthormi glacier and the supraglacial lakes considering different criteria like e.g. stage of the glacier retreat, increase of lakes in size and number, occurrence of dead-ice, occurrence of mass movements, stability of moraine dam, occurrence of seepages, erosion of the moraine dams by weathering and/or flooding and height difference between glacier lakes is reprinted in Table 2.1.

Based on the detailed assessment it was found that there is the probability for a worst-case GLOF hazard scenario in the near future (possibly occurring within the next ten years) originating in the Thorthormi area, having a very high impact on the Lunana villages and the downstream area.

Near the terminus of the **Thorthormi glacier a net of several interconnected supraglacial lakes** is developed. At present three large supraglacial lakes, one close to the unstable outlet area with a probable volume of 120.000 m³ and additional 20 smaller lakes were mapped. Due to **fast glacier melting** these **lakes are extending** rapidly and it is very probable that they will soon **form one large proglacial lake**. At present the hazard potential is low and **a possible outburst** will only result in a minor flood. But **in the near future** it can be of significantly higher magnitude, with a **downstream impact comparable to the 1994 Luggye GLOF event** (18 mill. m³). To mitigate the risk of a future GLOF originating at the Thorthormi lake the decision was taken by DGM/RGOB to widen the outlet channel within the next years.

Glacier	**Moraines**	**Outlet**
Fast decaying glacier snout. Supraglacial lakes expanding. Possible formation of large proglacial lake.	RLM stable. TM destabilized by seepages. LLM (Thorthormi-Raphstreng segment) shows sliding and is probably destabilized by melting ice lenses.	Steep active channel with landslides not capable to block the outlet. Seepages in the right sideslope. Possible reactivation of second outlet.
Assessed actual hazard potential	**Assessed hazard potential in the near future (<10 a)**	**Proposed mitigation measures**
Outburst of small supraglacial lake (6000 m³) is possible. No major impact on the downstream area.	Channel back cutting can result in liquefication and erosion of the channel bottom because of seepages triggering dam piping. After the formation of a proglacial lake (approx. size of Luggye lake) potential of a GLOF comparable to the 1994 Luggye event.	Monitoring program. In case of fast development of proglacial lake technical mitigation measures in the outlet. Hazard zonation plans, EWS.

Table 2.1: Results of the assessment of geo-hazard potential for the Thorthormi glacier and supraglacial lakes as executed by the Austro-Bhutanese team (modified after LEBER et al., 2002). RLM = right lateral moraine; LLM = left lateral moraine; TM = terminal moraine; Yellow shading = low hazard potential; red shading = high to very high hazard potential.

3 GEOMORPHOLOGIC AND GLACIER-GEOLOGIC CONDITIONS IN THE AREA OF THE PROPOSED TECHNICAL MITIGATION MEASURES

The decaying Thorthormi glacier is characterized by several supraglacial lakes spread over the distal part of the glacier. These lakes show a tendency to develop englacial conduits forming a big supraglacial to proglacial lake. During the field period 2000 to 2001 a quick expansion of the supraglacial lakes could be mapped and notable morphological changes indicate the increase of these glacial lakes.

The area around these glacier lakes, close to the terminal moraine, is characterized by an “undulated morphology” showing an intense creeping of slope debris and by collapsed, concave structures mostly filled with fine-grained sediments. Several small isolated ponds occur. Approximately 700 meters NW of the outlet in the terminal moraine rapidly melting ice cores feeding supraglacial lakes are outcropping, covered only by an up to 15 m thick debris. Below the debris cover a more or less continuous ice sheet with a thickness of more than 60 meters exists, what could be proved by geoelectric measurements.

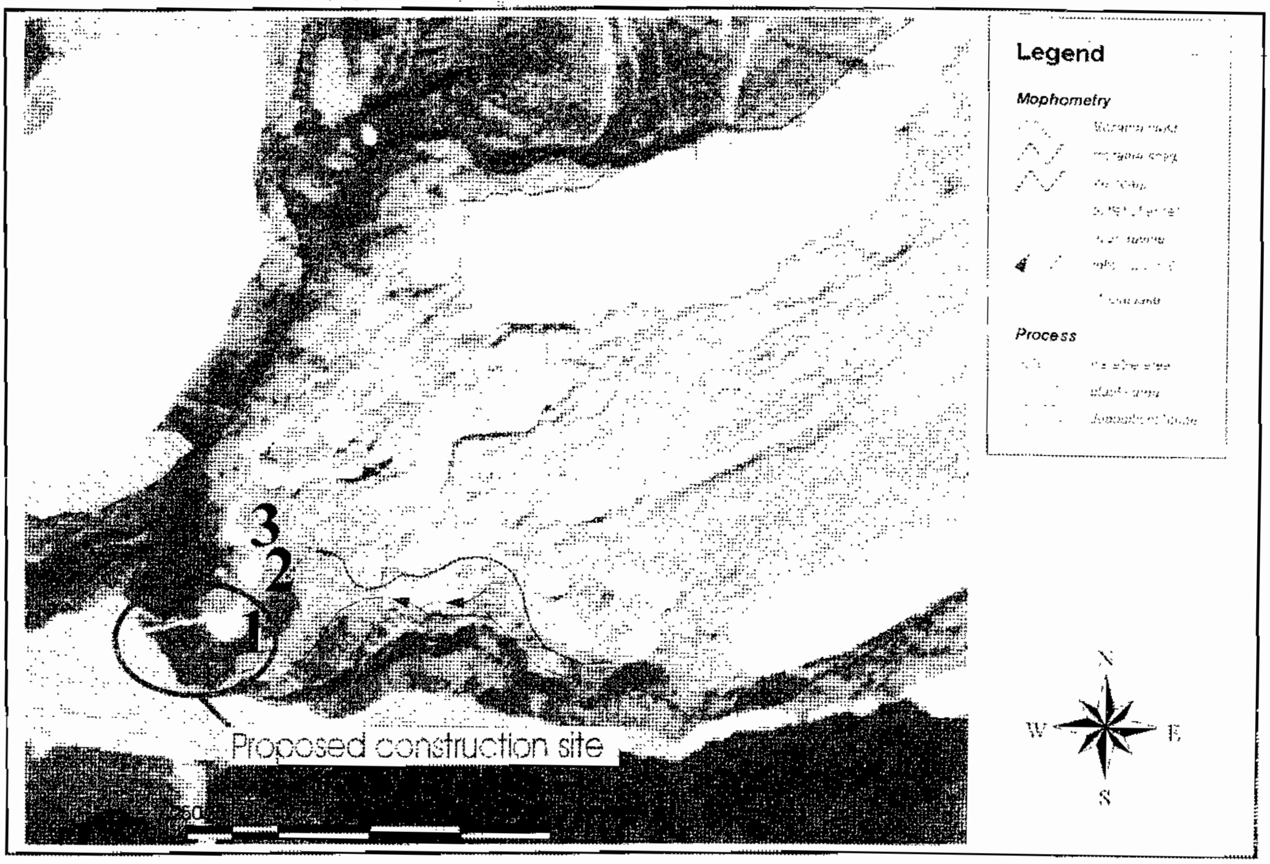

Figure 3.1: Present situation at Thorthormi glacier lake. Rapidly increasing supraglacial lakes (1-3) with a tendency to join to one proglacial lake in the near future. Proposed construction site along lake 1.

On the orographic right side of the glacier the active outlet channel is fed by three supraglacial lakes. On the orographic left side an inactive channel is present (relict channel, see Figure 3.1). It was inactive prior to 1994 and marks a supra/proglacial area, delineated by a ridge to the still active right part of the glacier.

The relict channel on the orographic left side is deeply incised into the terminal moraine. From its start at the ridge down to the moraine crest it is wide and gently sloped. Between the moraine crest and the Pho Chhu channel it steepens up - comparable to the active channel gradient (see Figure 3.2). This steep lower section is armoured by large boulders, but slides from the oversteepened sideslopes can result in blockage of the channel which may result in a small temporary lake (max. 2000 m³ volume) of neglectable risk potential. However the situation at both outlets and changes of the lakes and the ridge separating both outlets should be monitored on a yearly basis.

Comparing the hydrostatic profile of the lakes and of the outlet with the Pho Chhu river bottom level reveals, that at a distance of 550 m from the terminal moraine crest (measured from the active outlet), the glacier water level is below the Pho Chhu level. Therefore only the moraines in front of this level line can be at risk considering glacier drainage. As the glacier will lower its surface elevation due to melting this distance will shorten continuously. The same is true if the water level of the active outlet is lowered.

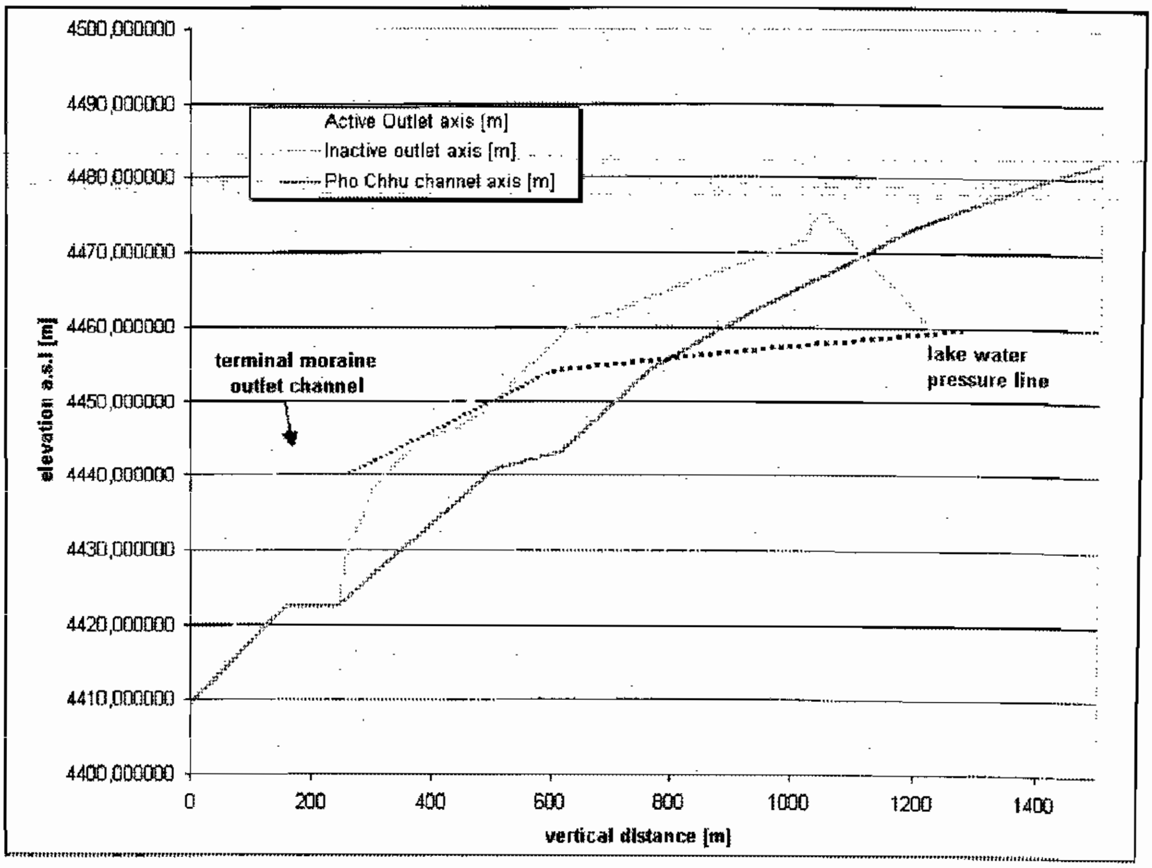

Figure 3.2: Longitudinal sections along inactive (orographic left) and active (orographic right) outlet channel of Thorthormi lake.

As Figures 3.3, 3.4 and 3.5 show, in 2001 the active spillway channel of the Thorthormi glacier is actively eroding into the moraine body. At that location the outer side of the 30 to 60 m high moraine body shows an average slope angle of 1:4, the inner side shows a more gentle slope of 1:10 (see Figure 3.4 and 3.5).

The spillway channel is very steep and shows big residual boulders (up to a diameter of 7 m) which can not be transported by water force. These residual boulders stabilise the spillway channel. Whereas the upper half of the channel is actively eroding, the lower part shows a lower slope gradient and can therefore be considered as stable.

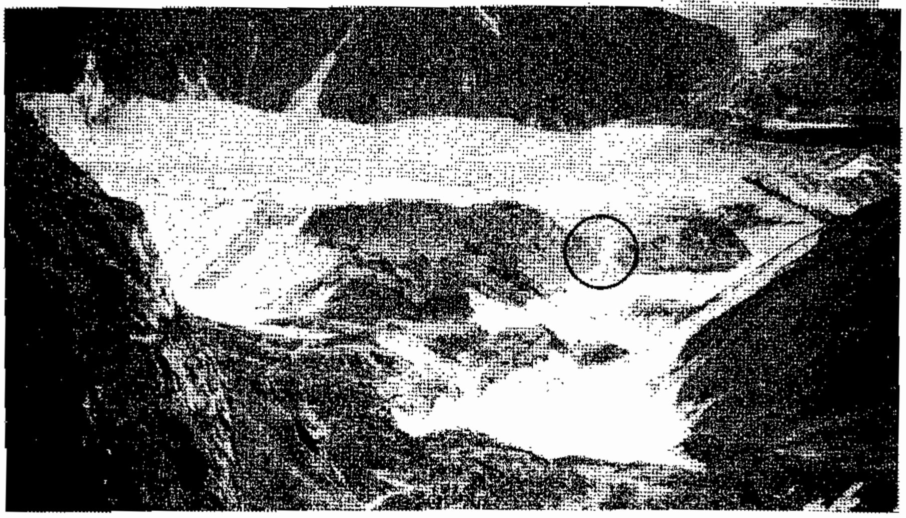

Figure 3.3: General overview on Thorthormi glacier, its active spillway channel and Raphstreng glacier lake on the left. Proposed technical mitigation measures (red circle).

Figure 3.4: Detailed overview of the Thorthormi spillway channel in summer 2001. Active sideslope erosion and big boulders stabilizing the channel can be seen.

Figure 3.5: Left: Lake outlet at the crest of the inner terminal moraine. Right: Lake inlet. On both sides features of the instable hummocky moraine are visible, probably underlain by dead ice.

4 PLANNED DESIGN OF THE OUTLET CHANNEL WIDENING BASED ON INFORMATION FROM THE PREVIOUS PROJECT

In contrary to the local situation encountered at other glacier lakes in the upper reaches of the Pho Chhu watershed, only for Thorthormi glacier lake a lowering of the water table by the excavation of an artificial channel (i.e. widening of the existing outlet channel) is feasible. This is due to the fact that the lowest (easternmost) Thorthormi proglacial lake has only a limited water volume of approx. 120.000 m^3. Additionally the outlet level is very high in respect to the crest of the moraines which results in low excavation cubature.

4.1 Available data and constraints

The planning and design of the technical mitigation measures presented in this report is based on topographic information and a Digital Elevation Model (DEM) generated from the Indian topo sheets (sheets no. 77 L/4 and 77 L/8; 1:50000), on high-resolution satellite imagery (IRS-1D) and on **engineering geodetic surveys** performed in summer 1999 in the course of engineering geophysical measurements (resistivity survey, seismics, ground penetration radar – see HÄUSLER et al., 2000) and taken during the field campaign in summer 2001 to evaluate the rapid extension of supraglacial lakes.

Due to the fact that **there never was the intention behind these measurements to provide very detailed topographic information required for the planning and execution of a technical project** – it is evident that the available geodetic survey data **can only serve as a rough basis** for the design of the technical mitigation measures in the Thorthormi area.

Normally – considering similar construction projects – a detailed survey at a scale between 1:20 and 1:50 is a prerequisite. Due to the special environmental conditions prevailing in the Thorthormi area (remoteness, altitude) and due to time constraints and financial constraints expressed by the Department of Geology and Mines (DGM), Royal Government of Bhutan (Director Dorji Wangda) – making a longer planning phase including field survey impossible – the Austrian expert group agreed to "take what is available" to sustain the DGM its mitigation activities.

Additionally to the topographic data all other information on geomorphology, hydrogeology and discharge, geotechnic parameters and subsurface composition collected during the previous project phases were used for this report. This information too was collected in less detail than normally required for site construction planning.

In the light of the above mentioned constraints the present report on proposed measures presented by the Austrian expert group can only serve as a rough guideline – the final responsibility for the technical mitigation activities at the Thorthormi lake rests with the Department of Geology and Mines /RGOB.

4.2 Stability assessment of the spillway channel

During the field campaign in summer 2000 and 2001 a short stability assessment was carried out. Based on the findings it can be concluded that the following factors may limit the long term stability of the active outlet:

- Steep outer slope of the moraine body of 1:4.
- Very steep upper part of the spillway channel of 1:2.8 – 1:3.2.
- A narrow spillway channel (5-6 m) which actively erodes.
- Small crest of the moraine body and spillway channel inlet.
- Seepages discharging lake or outlet water located nearby the lower channel

Based on these findings the following hazard scenarios can be outlined:

- At present the upper part of the spillway channel shows the risk for backcutting with consecutive destabilization and possible collapse of the small moraine crest and the sideslopes. Although temporal blockage is not probable due to the steep gradient of the channel, lateral erosion may cause additional risk and therefore need to be stabilized.
- Quick extension of the actual small lake. This will result in significantly higher water masses which will be prone to breach. Additionally the risk of surge waves, initiated by lateral mass movements impacting the enlarged lake will come into existence as high lateral moraines are adjoining the lake. All these processes can cause spillway erosion with consecutive dam breach.
- Increase of hydrostatic pressure is not probable as the lake already shows maximum possible water level, but the permeability of the moraine body may increase due to dead ice melting and intensified seepage activity.

5 DESIGN CONCEPT FOR THE SPILLWAY CHANNEL STABILIZATION

The lowering of the actual lake water level by excavating a trench through the moraine crest at the active spillway channel is suggested. To guarantee a stable trench the following conditions must be followed:

- Maximum channel bed slope of the trench at any phase of 1:20 (5 %) (see construction plan 1 and 2).
- During the excavation process bigger boulders must be removed by manual wrenches or by breaking them into smaller parts of about a size of 0.5 m (silent explosives). After the down-cut they are used for building up the armouring layer of the channel bed (see construction plan 7).
- Channel width 10 m, U-shaped and stabilized by boulders according to stability calculations. The armouring layer must be build up to a super-elevation of 2.5 m above the channel bottom. At the lower end of the armouring, stable foundations by means of big boulders and/or gabion caskets must be established (see construction plan 7).
- A maximum sideslope angle of 2:3 (66 %) on both sideslopes of the trench and the spillway channel must be maintained. Sideslope stability must be provided at any phase! (see construction plan 3, 4, 5 and 6).

- The lowering can be achieved in excavation steps of not more than 2 m each, till the lake water level has been lowered by 5 m (see construction plan 2).
- Due to the limited time and very rough working conditions all potentially "wet work" (i.e. below the channel water line) should be carried out in dry conditions by establishing water diversion with the help of a cofferdam at the channel inlet and a lake drainage trough two water pipes. For each down cutting phase a cofferdam according to the plan in the annex should be established (see construction plan 8).

In detail each excavation step consists of the following work steps:

1. Establishment of water diversion by building up the coffer dam with pipe conduits.
2. Establishment of stable sideslopes on both sides according to the cross section indicated in the cross section plans A-A to D-D in the annex.
3. Widening of the channel bed according to the cross section plans.
4. Lowering of the channel bed according to the cross section plans.
5. Opening of the coffer dam (not at pipe location), erosion of the dam by water force and shift of the coffer dam to the new lake water shore line.
6. After the base level of the trench is established the armouring layer can be build up starting at the lower end of the trench with the foundation. Also for this procedure water diversion is recommended!

5.1 Risks and restraints

As the actual surface slope and maximum depth below the lakes waterline is not known, only assumptions can be made. Therefore the following calculations are based on the assumption of a subwater-surface slope angle of 1:10 and a lake depth of 5 m.

The seepage located right of the lower channel section (see Figure 3.4) limits the available down cutting depth of the trench. Therefore during the whole work attention should be drawn to seepages and a maximum cutting depth of 8 m at the moraine crest (section A-A) should not be exceeded.

5.2 Water diversion

In order to carry out all channel works in dry conditions water diversion is recommended. This can be achieved by a coffer dam at the channel inlet consisting of compacted moraine sediment smaller than 20 mm. Assuming a design discharge during the work period of 4 m^3/s the water can be diverted through two PE pipes with diameters equal to 0.8 m through the coffer dam and the trench.

Due to the fact that there exists only one single discharge measurement, done with the salt-dilution method on September 16, 2001 at 14.28, giving a value of 3.75 m^3/sec (see LEBER et al., 2003:Table 3.4.2.1) the maximum discharge can only be approximated using other time series of discharge measurements available from other lakes in the Lunana area.

The calculation of the necessary pipe dimensions were carried out according to VISCHER & HAGER (1998), assuming a PE pipe which protrudes without headwall into the lake. The dam shows a crest width of 3 m, a crest height of 4 m (relative to the pipe inlet bottom) and sideslopes of 1:2. The dam is build by compacted dam material - each time a layer of 0.1 to 0.2 m is deposited and manually compacted. To guarantee a down-cutting depth of 2 m for each construction step, the dam has to be built in a U-shaped alignment around the outlet intake. The dam must protrude into the lake to an extent that the pipe conduit bottom is located 2 m below the actual channel intake bottom level. The dam height of 4 m is necessary to get a freeboard of 2 m (for wave action and short intensified water discharge).

For the construction of the coffer dam locally available sediments (available from excavation) can be used. According to the analysis of three sediment samples taken from the moraines of the Raphstreng lake (close to Thorthormi) by the Geological Survey of India (WAPCOS, 1997) during the year 1996 expedition, the moraine material can be classified as GM (silty gravel)/GC (clayey gravel) according to the USCS (Unified Soil Classification System) classification which is suitable for homogenous dam construction (CADENAS DE LIANO, 1993). In detail the following distribution of the grain sizes needed for the construction of the coffer dam can be deduced (see Table 5.1 and Figure 5.1).

Grain size in mm	Quantity needed (USCS) in percent	Quantity available in percent	Total quantity of grain sizes < 20 mm
< 0.002	2 – 9	0.4 - 1.3	Taken from three sediment samples
0.002 – 0.05	6 – 23	1.6 - 4.7	
0.05 – 0.2	13 – 24	4 – 11	
0.2 - 2	2 – 19	13 - 27	
2 - 20	20 – 52	18 - 34	**54 to 60 %**

Table 5.1: Grain size distribution and expected quantity of moraine sediments (55 to 60 %) available at the construction site which can be used for the construction of the coffer dam. Information based on grain size analysis of three sediment samples taken by GSI at the Raphstreng lake in 1996 (WAPCOS, 1997).

During the work period a maximum outflow of 4 m^3/s at maximum is assumed. In order to divert this discharge through the trench, two PE pipes with a diameter of 800 mm each are needed (e.g. PE Weholite Spiro low pressure pipes). The pipes need to be fixed to a seal collar consisting of two metal rings (max. diameter 2 m), tightly fitting around the pipes. The total length of the pipes is estimated as 130 m (max. length of the trench). The pipes need to be fixed each 10 m by gabions on each side.

5.2.1 Risks and restraints

There should be none of them. As the coffer dam is small also unplanned overtopping will not destabilize the actual outlet channel. A good bedding of the pipes is very important. Therefore a filter layer of fine material should be thoroughly worked around them and the seal collars.

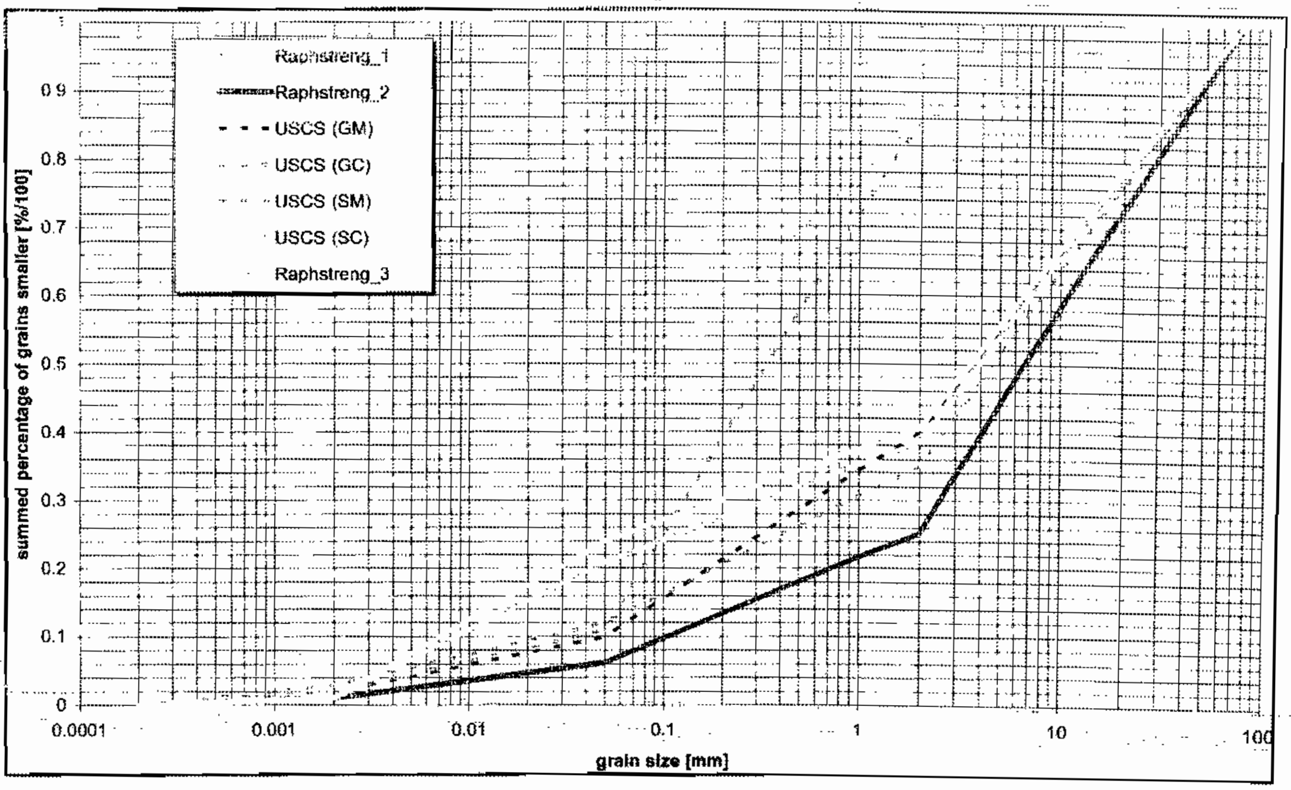

Figure 5.1: Comparison between measured grain size distribution (solid lines) of the Raphstreng moraine and grain size distributions suitable for homogenous dam construction according to unified soil classification system (USCS). GM – Silty gravel, GC – Clayey gravel, SM – Silty sand, SC – Clayey sand.

5.3 Sideslope/channel stabilization

Based on the cross section plans A-A to D-D for each step the final cross sectional width is set out. Then the suggested slope is established starting from the top, simultaneously lowering the sideslope in steps not more than 2 m. Whereas the finer material (smaller than 20 mm) can be used for the coffer dam or can be washed down by the spillway flow, all bigger diameters have to be deposited. All boulders with a diameter bigger than 0.5 m will be needed for channel stabilization later on. All other excavation material has to be dumped. For this task small cable cars can be used.

After stable sideslopes (significantly lower than 2:3) are established, the channel bottom is widened according to the cross section plans A-A to D-D. After this step both sideslopes should reach a slope angle of 2:3. At that time the coffer dam should be closed and the lake water diverted through the pipes. As a next step the channel bottom can be lowered according to the cross sectional profiles A-A to D-D.

5.3.1 Risks and restraints

If the work proceeds according to the plans no significant risks have to be considered. Bigger boulders have to be cracked up by silent explosives down to an average diameter that they can be used for channel armouring. In case of seepages a hydrogeological expertise should check for stable conditions. Big residual boulders (bigger than 2 m in diameter) can remain in the channel section provided that they are well bedded and the armouring layer is build tightly around them.

6 CHANNEL STABILIZATION MEASURES

In order to guarantee a stable channel bed the maximum channel gradient is assumed to remain below 5 % with a channel width around 10 m. The average boulder diameter needed to maintain a stable channel bed is calculated according to WHITTAKER & JAEGGI (1986). For this calculation a high water discharge of 40 m³/s, similar to the discharge estimated for Luggye Tsho (LEBER et al., 2001) is considered.

Design discharge [m³/s]	40	
D50 of moraine material [m]	0.10	
Channel width [m]	10	
Channel slope [m/m]	0.35 (old channel)	0.05 (new trench)
D65 of armouring layer [m]	1.3 – 1.5	0.3 – 0.4
Armouring layer thickness [m]	1.9	0.6
Armouring layer stable?	yes	yes

Table 6.1: Design parameters for armouring layer (part 1).

Boulder weight per square meter [t/m²]	1.2
Boulder volume per square meter [m³/m²]	~0.5
Boulders per square meter [Pcs./m²]	~40, at an average diameter of 0.4 m
Armouring layer length [m]	130
Armouring layer width [m]	15
Armouring layer area [m²]	1950
Armouring layer total volume [m³]	975

Table 6.2: Design parameters for armouring layer (part 2).

After the construction of the trench, the upper, newly established channel section will show a channel gradient of 5%, whereas the lower, original section still shows a gradient for about 35%. Therefore the erosion protection of the upper channel section will need smaller boulders as indicated in Table 6.1 and Table 6.2. According to the calculation based on a design discharge of 40 m³/s for the new trench armouring layer, boulders with an average size of 0.5 m and a boulder volume of 0.5 m³ per m² are needed. The steeper unaltered channel section below still needs an armouring boulder size of 1.5 m (see Table 6.1). As most parts of this channel section show sufficient boulder size only some areas with significantly smaller boulders sizes have to be reinforced punctually. To guarantee good armouring the individual boulders must be built in, starting at the lower end with their longest axis in vertical to slight upstream orientation. On both channel sides the armouring layer must be extended up to the high water line which is 2.5 m above the channel axis . As the boulders must be built in very close to each other, an average porosity of the armouring layer of 30 % is estimated. Due to the variable sediment sizes of the moraine no fine filter layer is needed. The well prepared moraine material (no hollows, slightly compacted) can function as foundation of the armouring layer. To guarantee a stable foundation at both ends of the armouring section the armouring layer must be interconnected with big residual boulders, or a gabion wire fixing the armouring layer must be established at the end of the stabilization measures (see construction plan 1).

6.1 Risk and restraints

The dense and stable assembly of the armouring layer is very important. Therefore the average size and position of the boulders must be checked and some excess boulders can be stored aside to be quickly available in case of damage.

7 EXCAVATION VOLUME, CONDITIONS OF EXCAVATION WORKS AND NECESSARY PRECAUTIONS TO BE TAKEN

Based on the length of the trench and its cross section area, the sediment volume needed for the coffer dam and the armouring layer and the total excavation volume was calculated (see Table 7.1 and Table 7.2). Like indicated in the tables more sediment is needed for the construction of the coffer dam than can be provided by trench excavation. Therefore additional sediment has to be excavated nearby the dam construction site. In contrary to the insufficiently available smaller grain sizes enough boulders bigger than 0.5 m will be available from the trench excavation. Therefore it is guaranteed that an armouring layer of approx. 1900 m² can be constructed with boulders having a total volume of 950 m³.

In total a volume of nearly 34500 m³ will have to be excavated from the trench and additional 8000 m³ will have to be excavated to provide sufficient sediments showing smaller grain sizes (< 20 mm) for the construction of the coffer dam.

	Section 00	reach	Section AA	Reach	Section BB	Reach	Section CC	Reach	Section DD	Reach	Section EE	Sum [m]
Channel length between sections [m]		77		6		25		20		31		
Section channel width [m]	10		12		10		10		10		10	
Section area of channel subsection [m²]		340		55		190		55		0		
Section area of sideslope subsection [m²]	0		345		345		320		31		0	
Excavation volume of channel subsection [m³]		3,740		605		1,900		550		0		6,795
Excavation volume of sideslope subsection [m³]		13,265		2,070		8,379		3,475		474		27,663
Total excavation volume [m³]												34,458

Table 7.1: Calculation of the total excavation volume.

8 CONDITION OF EXCAVATION WORKS AND NECESSARY PRECAUTIONS TO BE TAKEN

In summer 1999 engineering geophysical surveys were carried out in the area of the terminal moraine/outlet area of the Thorthormi glacier/lakes to locate the extension of dead ice bodies or dead ice lenses and to assess the sedimentary composition (see HÄUSLER et al., 2000). The following conclusions can be drawn with respect to the forthcoming excavation works in this area:

- Outlet channel and terminal moraine: From the seismic refraction measurements along the terminal moraine, perpendicular to the outlet channel (see HÄUSLER et al., 2000:Figure 6.3, Profile S3) it can be interpreted that in the outlet channel area a up to 10 meters thick surface layer mostly composed of boulders is underlain by coarser grained debris including boulders and clusters of boulders. This layer has a thickness of up to 30 meters. The presence of dead ice in the outlet area can be ruled out to a great extent although the deeper seismic sections could not be interpreted due to the occurrence of seismic noise.
- Area between terminal moraine and end of moraine dammed glacier lake: The area around the easternmost moraine dammed glacier lake shows an "undulated morphology" representing the ablated moraine with melted ice cores. From reflection seismics and geoelectrics (see HÄUSLER et al., 2000: Figure 3.3) along two NNW-SSE directed profiles approx. 700 m West of the outlet it can be concluded that the large debris-covered areas close to the terminal moraine are still ice-cored although the extension towards the glacier lake is uncertain. The occurrence of dead ice between the glacier lakes cannot be excluded.

	Cross section	OO		AA		BB		CC		DD	Sum
Step 1	Channel length between sections		15		6		25				
	section area sideslopes [m²]	0		43		45		0		0	
	section area channel [m²]	0		21		22		0		0	
	Excavation width for each section [m]		See map 3 - 6								
	Excavation depth for each section [m]		See map 3 - 6								
	Total volume excavated		637		399		567		0		**1,603**
	Usable volume for coffer dam (1)		86		71		151		0		**308**
	Usable volume for armouring (2)		64		40		57		0		**160**
	Volume needed for coffer dam (3)		1,828						0		**1,828**
Step 2	Channel length between sections		30		6		31		4		
	section area sideslopes [m²]			45		43		43		0	
	section area channel [m²]			23		22		22		0	
	Excavation width for each section [m]		See map 3 - 6								
	Excavation depth for each section [m]		See map 3 - 6								
	Total volume excavated		1,360		396		2,015		87		**3,857**
	Usable volume for coffer dam		734		214		1,088		47		**2,083**
	Usable volume for armouring		136		40		202		9		**386**
	Volume needed for coffer dam		3,656								**3,656**
Step 3	Channel length between sections		50		6		31		12		
	section area sideslopes [m²]			60		60		60		0	
	section area channel [m²]			30		30		30		0	
	Excavation width for each section [m]		See map 3 - 6								
	Excavation depth for each section [m]		See map 3 - 6								
	Total volume excavated		2,999		538		2,782		360		**6,679**
	Usable volume for coffer dam		1,620		291		1,502		194		**3,607**
	Usable volume for armouring		300		54		278		36		**668**
	Volume needed for coffer dam		6,094								**6,094**
Step 4	Channel length between sections		70		6		31		15		
	section area sideslopes [m²]			73		73		73		0	
	section area channel [m²]			37		37		37		0	
	Excavation width for each section [m]		See map 3 - 6								
	Excavation depth for each section [m]		See map 3 - 6								
	Total volume excavated		5,132		660		3,410		550		**9,752**
	Usable volume for coffer dam		2,771		356		1,841		297		**5,266**
	Usable volume for armouring		513		66		341		55		**975**
	Volume needed for coffer dam		8,531								**8,531**

Cofferdam	Assumption: 1 time the length of the trench starting at A-A, plus cross section	65	m²
	Compaction of dam material	0.250	%/100
Sediment fraction usable for dam construction		0.540	%/100
Sediment fraction usable for armouring		0.100	%/100

Quantity of dam construction material insufficient — 5000 m³ have to be additionally supplied

Quantity of armouring boulders available at construction site sufficient

(1) Excavatable volume of sideslopes above the channel water line (prior to establishment of coffer dam)
(2) Volume of boulders of sufficient size accessible after establishment of coffer dam (sideslope and channel bottom)
(3) Volume needed at dam construction site considereing compaction

Table 7.2: Calculation of excavation volume for trench, coffer dam and armouring layer. The calculations are based on the cross section plans and the assumptions listed above. The last column (bold numbers) gives the excavation volume and the needed volume for water diversion work and armouring for each excavation step. For all steps the material needed for the coffer dam exceeds the excavated material at the trench. Therefore additional material of approx. 8000 m³ is needed!

9 CALCULATION OF NECESSARY WORK FORCE AND TIME TO FINISH THE WORK

As there is only very limited risk in destabilizing the channel by the mitigation measures proposed, the work can be carried out extensively over several working periods with local people.

Due to the climatic conditions prevailing in the construction area the time window between mid of May and mid of October (onset of snowstorms blocking the high passes) should be used for the construction activities.

Due to the harsh conditions in Lunana (climate, altitude) **the weekly working time must not exceed 5 days. Medical service for the workers must be available** at the site. Especially trained personnel should check the physical condition of every worker in the morning and evening to **avoid serious problems due to high altitude sickness** – which already claimed lives during the outlet channel widening at the Raphstreng Tsho (personnel comm. Yeshi Dorji) and during the Austro-Bhutanese GLOF Mitigation expeditions.

Based on the experience of the mitigation works executed at the Raphstreng lake – where large parties with more then 400 workers led to serious social problems in the small villages and to an environmental degradation (excessive use of firewood) – the number of persons engaged in the mitigation works at the Thorthormi should be limited with approx. 300 workers. That means that in total **20 working groups consisting of 14 workers and one supervisor can be deployed**.

Given a sufficient supply with technical equipment and construction material and given an adequate provision, the technical mitigation work at the Thorthormi outlet **can be executed within 4 field seasons** (see Table 9.1).

		Workforce excavation	Workforce transport	workforce coffer dam	Workforce armouring	Workforce Total
Step 1	Excavation	11,539				11,539
	Coffer dam	31,460	13,711	14,854		60,024
	Armouring					0
	Total					**71,563**
Step2	Excavation	27,773				27,773
	Coffer dam	32,550	27,422	29,707		89,679
	Armouring					0
	Total					**117,452**
Step 3	Excavation	48,092				48,092
	Coffer dam	51,452	45,703	49,512		146,667
	Armouring					0
	Total					**194,759**
Step 4	Excavation	70,217				70,217
	Coffer dam	67,552	63,984	69,316		200,852
	Armouring				13,300	13,300
	Total					**284,369**
	Total sum of manhours					**668,144**
	Total sum of mandays with 8 houres					**83,518**
	Total sum of mandays assuming persons				**300**	**278**
	Total sum of weeks (5 workdays each)					**56**
	Total sum of seasons (17 weeks each)					**3.3**
	+20 % Unforeseen delay/sick leave					**4.0**
	Person houres:					
	Excavation of 1m³ moraine (in situ) + blasting					6.0
	Transport of 1m³ material to coffer dam					6.0
	Construction of 1 m³ coffer dam					6.5
	Armouring layer construction (1m3)					14.0

Table 9.1: Calculation of the man power needed during 4 excavation steps (step 1-4). The assumed time per m³ soil or boulders (second row) is based on experience. Person hours according to ACHARYA (1999). In total 4 seasons (= 4 years) are required to complete the Thorthormi spillway channel.

10 NECESSARY TECHNICAL EQUIPMENT AND MEANS TO REMOVE LARGE BOULDERS

10.1 Proposed technical equipment

The following technical equipment for one working group (14 workers and 1 supervisor) is proposed. This results in a technical equipment load per working group of approx. 140 kg (see Table 10.1).

Tool	Approx. weight	Quantity per group
Water vessel 20l (garo)	2.75	1
Pick-axe (Khanti)	5.0	1
Axe (Bancharo)	2.5	1
Baskets (Doko)	2.0	18
Chisel (Chinno)	2.0	4
Crowbar small (gar)	4.5	1
Crowbar medium (gal)	7.0	1
Crowbar large (gal)	11.0	1
Frog and feathers	0.5	3
Hammer large (ghan)	4.5	1
Hammer medium (ghan)	2.3	1
Hammer small (ghan)	1.0	2
Mason's hammer (Mairi)	1.0	2
Pick (Gainti tata)	2.5	6
Shovel (Blecha)	2.5	6
Spate (Kuto)	1.75	6
Tape 30 m (Phitta)	0.75	1
Rope (Dori) 50 m	8.0	1
Trowel (Jyawal)	0.3	1
Sieve 1x1m, 20mm mesh for dam material	10	3
Claw pull 1 ton	20	1
Steep cable (10mm diameter) with cashions	20	1

Table 10.1: Proposed technical equipment (tools) for one working group.

In addition to the technical equipment mentioned above, two simple cable cars or 2 wooden slides are proposed. Table 10.2 gives the technical description of this equipment.

Cable car (approx. 650 kg each)
12 mm steel cable (main cable) 100 m (80 kg – one piece)
10 mm steel cable 100 m (70 kg – one piece)
Wooden car for 100 kg total load (2 x 25 kg)
1 Manual or motor wrench (100 kg)
6 steel plates to fix the cables with 7 holes (4 cm diameter) each; 36 steel pitons diameter 3 cm, length 1.5 m (13 x 25 kg)
1 Claw pull 1.5 tons (25 kg)
Other equipment
4 seal collars (steel, outer diameter 2 m, inner diameter: tightly fitting the pipes, 1 cm thickness) – (4 x 90 kg)
15 gabions (1 x 1 x 2 m) – (15 x 20 kg)

Table 10.2: Additional technical equipment needed (cable cars or wooden slides).

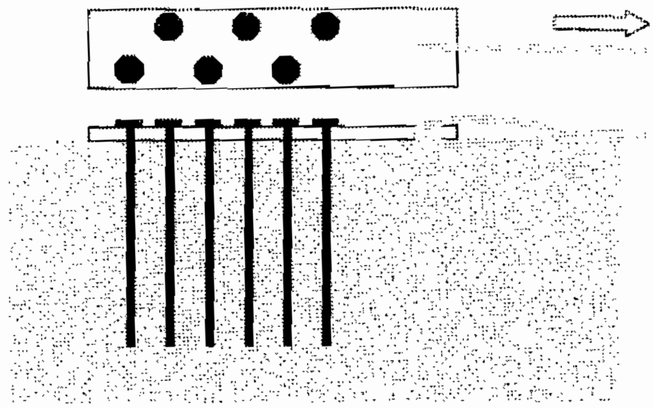

Figure 10.1: Sketch of the steel plate to fix the cable (cable car) to the ground. Upper image: vertical view, lower image: side view. steel pitons (black), steel plate (blue), steel cable (gray).

10.2 Means to remove large boulders

The removal of large boulders with shovels, crowbars or ropes is a big problem as seen during the construction work at the Raphstreng lake. Like during the previous phase it is advised to use silent explosives to crack the boulders. The necessary drilling equipment for the boreholes to be filled with the silent explosives must be available.

In the case that a certified blaster is available during the field work regular blasting of big boulders is possible. In that case the quantity of explosives used must be observed thoroughly to avoid too strong shock waves destabilizing moraine bodies or sideslopes.

11 PRELIMINARY CALCULATION OF THE COST

Based on the information available from the previous technical mitigation measures executed by an Indo-Bhutanese team at the Raphstreng lake in 1996 and 1997 (WAPCOS, 1997) and on the experience gained during the Austro-Bhutanese expeditions to the Lunana and Tarina area a preliminary calculation of the cost for the four working periods was performed.

This calculation can only serve as a first basis – a more thorough calculation of the cost has to be done by the Department of Geology and Mines. The cost of many different items listed in Table 11.2 had to be assumed due to the fact that detailed data is missing. Especially the cost for the acquisition of the PE low pressure pipes and for their transportation by helicopter to the construction site can only be guessed. The different Asian companies producing PE pipes or operating helicopters will have to be asked for detailed quotations.

The preliminary calculation of the cost shows that to cover the cost for the first phase approx. 39 million (NU 38942400) Ngultrum are required what approx. equals 739000 EURO). The other three phases require approx. 27,6 million (NU 27558240) Ngultrum each (what equals approx. 523.000 EURO).

The total cost to finish the technical mitigation measures at the Thorthormi lake is assumed to be **121.6 million Ngultrum, what equals approx. 2.3 million EURO.**

PRELIMINARY CALCULATION OF COST IN NGULTRUM (NU)		
ITEM	REMARK	AMOUNT
FIRST WORKING PERIOD		
Labour cost		
300 workers – onward journey	8 days x 150 NU/day = 1200	360000
300 workers – return journey	8 days x 150 NU/day = 1200	360000
300 workers in the field	Mid of May to beginning of October = approx. 170 days x 300 NU/day = 51000	15300000
3 overseers	200 days x 600 NU/day = 120000	360000
3 cooks	200 days x 600 NU/day = 120000	360000
10 kitchen helpers	200 days x 200 NU/day = 40000	400000
Medical service	Assumed based on information from Raphstreng lake mitigation measures	400000
D.A. for RGOB Officers/staff	Assumed based on information from Raphstreng lake mitigation measures	200000
Transportation cost		
Yaks/horses onward and return	assumed party of 330 people – 1 load/person = *330 loads*; 35 community/kitchen tents – 2 loads/tent = *70 loads*; kitchen equipment – *50 loads*; assumed provision (1500 kg) – *60 loads*; assumed technical equipment – 6 loads per working party x 20 = *120 loads*; 2 cable cars dismantled – *70 loads*; additional technical equipment, power generators and fuel – assumed *50 loads*; Medical equipment – *10 loads*; Total number of loads – 760 = 380 yaks or horses x 400 NU = 152000 x 16 days = 2432000	2432000
Transportation in the field	Assumed based on information from Raphstreng lake mitigation measures	50000
Helicopter transport of PE pipes	60 pipes; length 5 m; weight of one pipe 125 kg; carrying capacity of commercial helicopter reduced to 250 kg (due to altitude); 2 pipes per flight can be shifted; flight time approx. 1 hour tour/retour; total needed operation time 30 hours. Approximate cost based on experience of the Austrian team.	4200000
PE low **pressure pipes**	300 meters, dimension 0.8 m; assumed cost/meter 3600 NU (check with companies operating in Asia)	1080000
Medical equipment	Assumed based on information from Raphstreng lake measures	250000
Provision	Assumed based on information from Raphstreng lake mitigation and Austrian expeditions	1500000
Technical equipment	Assumed based on information from Raphstreng lake measures	4000000
Rental charges, insurance	Assumed based on information from Raphstreng lake measures	1000000
Improvement in trekking route	Assumed based on information from Raphstreng lake measures	200000
Contingencies	Assumed based on information from Raphstreng lake mitigation and Austrian expeditions 20 %	649040
	ASSUMED TOTAL COST OF FIRST PHASE (approx. 739000 EURO)	**38942400**

Table 11.1: Preliminary calculation of the cost of the technical mitigation measures (part 1).

PRELIMINARY CALCULATION OF COST IN NGULTRUM (NU)		
ITEM	**REMARK**	**AMOUNT**
SECOND WORKING PERIOD		
Labour cost		
300 workers – onward journey	8 days x 150 NU/day = 1200	360000
300 workers – return journey	8 days x 150 NU/day = 1200	360000
300 workers in the field	Mid of May to beginning of October = approx. 170 days x 300 NU/day = 51000	15300000
3 overseers	200 days x 600 NU/day = 120000	360000
3 cooks	200 days x 600 NU/day = 120000	360000
10 kitchen helpers	200 days x 200 NU/day = 40000	400000
Medical service (1 doctor and one assistant)	Assumed based on information from Raphstreng lake mitigation	400000
D.A. for RGOB Officers/staff	Assumed based on information from Raphstreng lake mitigation	200000
Transportation cost		
Yaks/horses onward and return	assumed party of 330 people – 1 load/person = *330 loads*; 10 community/kitchen tents (replacement) – 2 loads/tent – *20 loads*; kitchen equipment – *20 loads(replacement)*; assumed provision (1500 kg) – *60 loads*; additional technical equipment and fuel – assumed *50 loads*; Medical equipment – *5 loads*; Total number of loads – 485 = 243 yaks or horses x 400 NU = 97200 x 16 days = 1555200	1555200
Transportation in the field	Assumed based on information from Raphstreng lake mitigation	20000
Medical equipment	Assumed based on information from Raphstreng lake mitigation	50000
Provision	Assumed based on information from Raphstreng lake mitigation and Austrian expeditions	1500000
Technical equipment	Assumed based on information from Raphstreng lake mitigation (replacement)	1000000
Rental charges, insurance	Assumed based on information from Raphstreng lake mitigation	1000000
Improvement in trekking route	Assumed based on information from Raphstreng lake mitigation	100000
Contingencies	Assumed based on information from Raphstreng lake mitigation and Austrian expeditions 20 %	4593040
	ASSUMED TOTAL COST OF SECOND PHASE (approx. 523000 EURO)	**27558240**
3rd WORKING PERIOD	**ASSUMED TOTAL COST OF THIRD PHASE (approx. 523000 EURO)**	**27558240**
4th WORKING PERIOD	**ASSUMED TOTAL COST OF FOURTH PHASE (approx. 523000 EURO)**	**27558240**
ASSUMED TOTAL COST FOR ALL FOUR WORKING PHASES		
	(approx. 2308000 EURO)	**121617120**

Table 11.1: Preliminary calculation of the cost of the technical mitigation measures (part 2)

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15 ANNEX I

Construction plan 1: Thorthormi Tsho Spillway Channel – Trench with armouring.

Construction plan 2: Thorthormi Tsho Spillway Channel – Longitudinal section.

Construction plan 3: Thorthormi Tsho Spillway Channel – Cross section A-A.

Construction plan 4: Thorthormi Tsho Spillway Channel – Cross section B-B.

Construction plan 5: Thorthormi Tsho Spillway Channel – Cross section C-C.

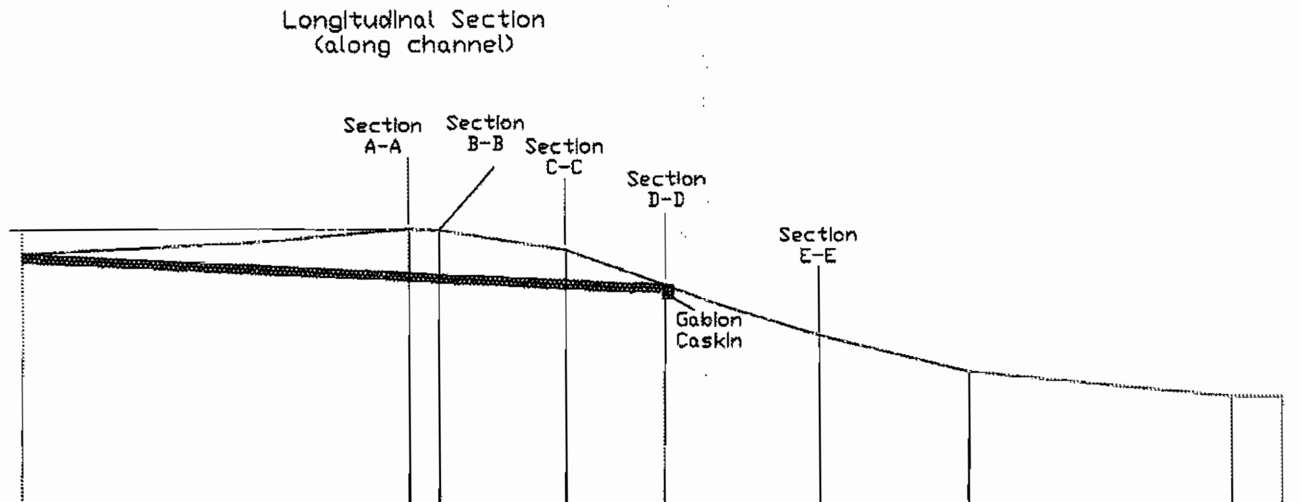
Construction plan 6: Thorthormi Tsho Spillway Channel – Cross section D-D.

Construction plan 7: Thorthormi Tsho Spillway Channel – Armouring layer – cross section.

Construction plan 8: Thorthormi Tsho Spillway Channel – Coffer dam.

Construction plan 9: Thorthormi Tsho Spillway Channel – Construction details of final trench and alignment of coffer dams draped on IRS-1D satellite image.

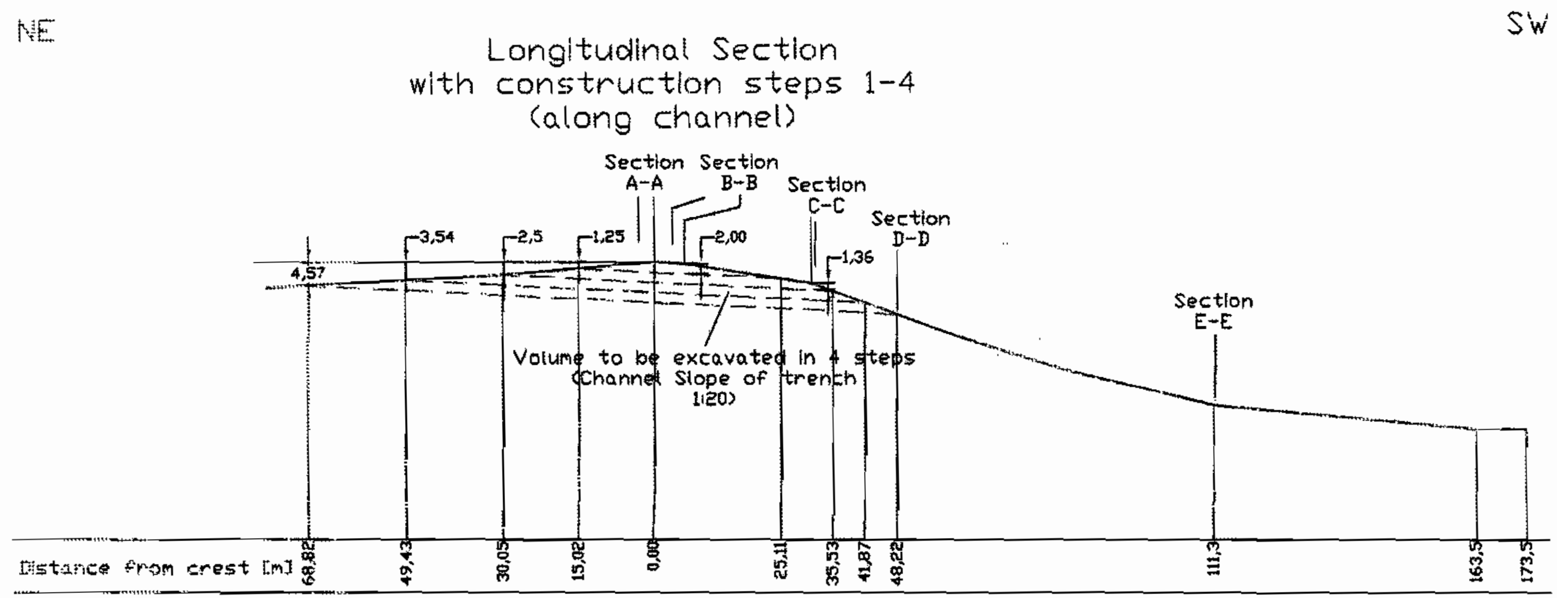
NE SW



Distance from crest [m]	76,9	0.0	6.0	31,2	51.0	81.6	111,3	163,5	173,5
Actual channel bottom elevation [m]	28,5	33,5	33,2	29,3	22,11	12.0		0.0	0.0
New channel bottom elevation [m]	28,5	24,6	24,36	23,1	22,11				

Elevations relative to Pho Chhu river level

Thorthormi Tsho
Spillway channel
Trench with Armouring
Construction plan 1
Scale 1:1500
Measurement units in m

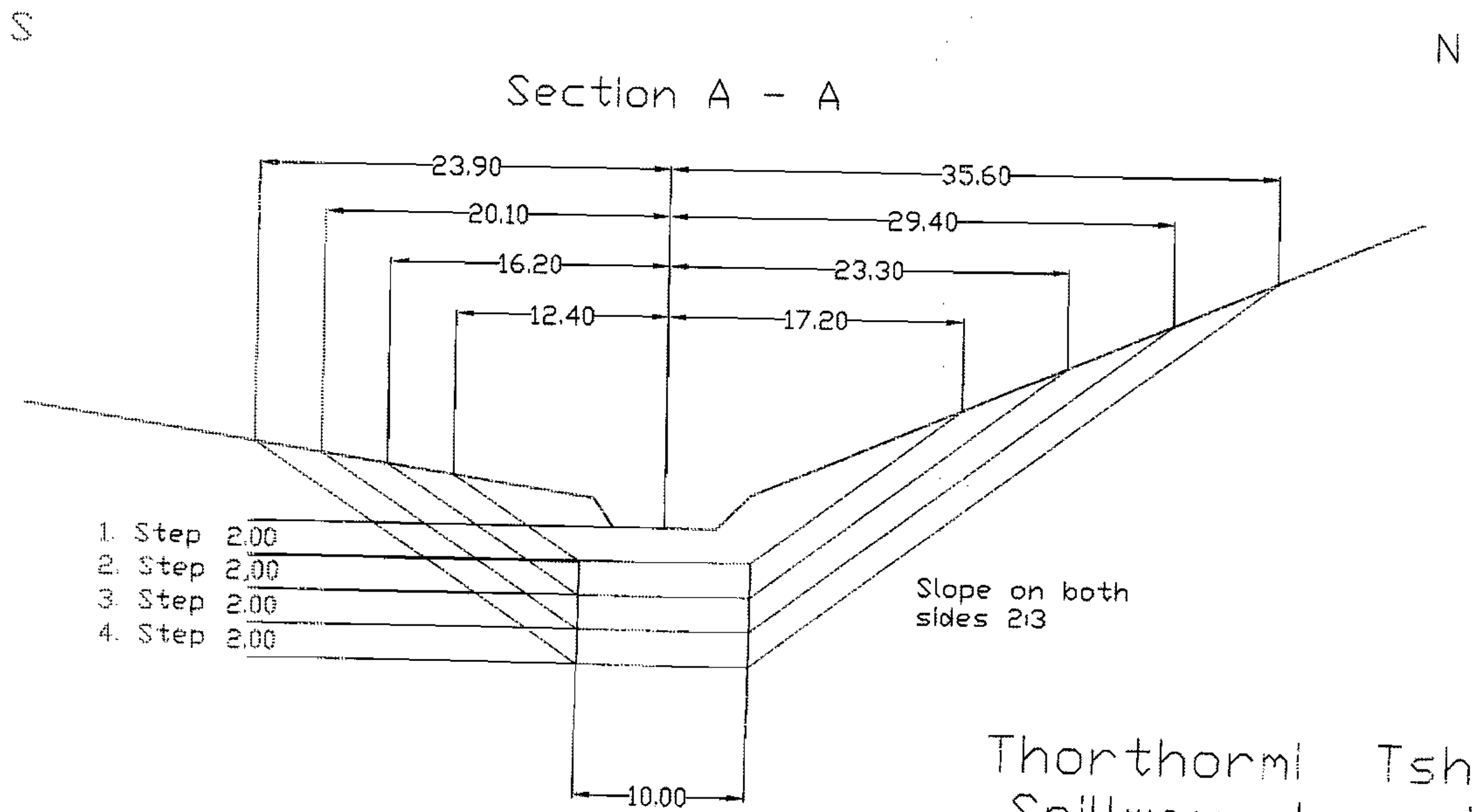


Thorthormi Tsho
Spillway channel

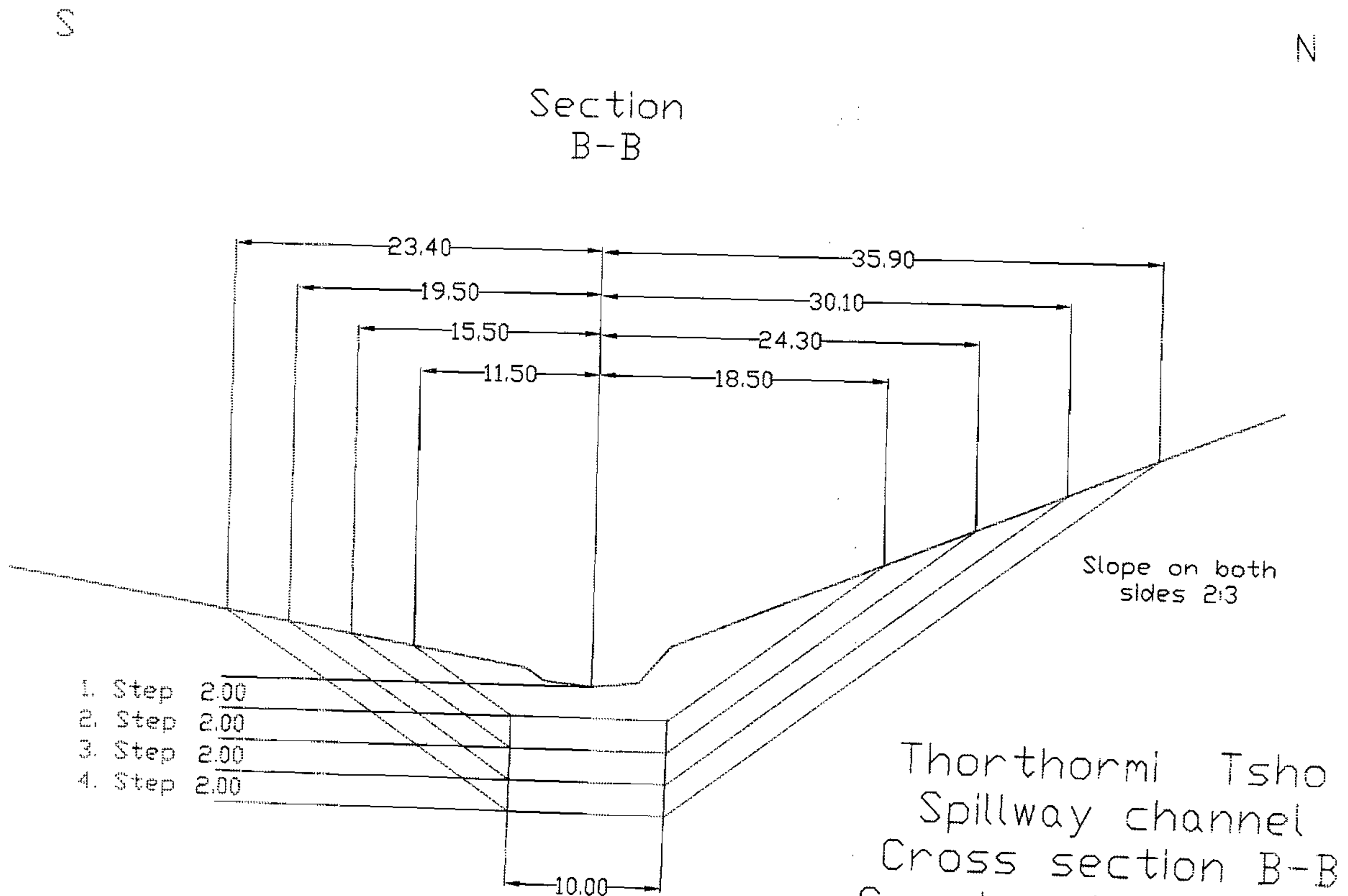
Longitudinal Section
Construction plan 2

Scale 1:1500

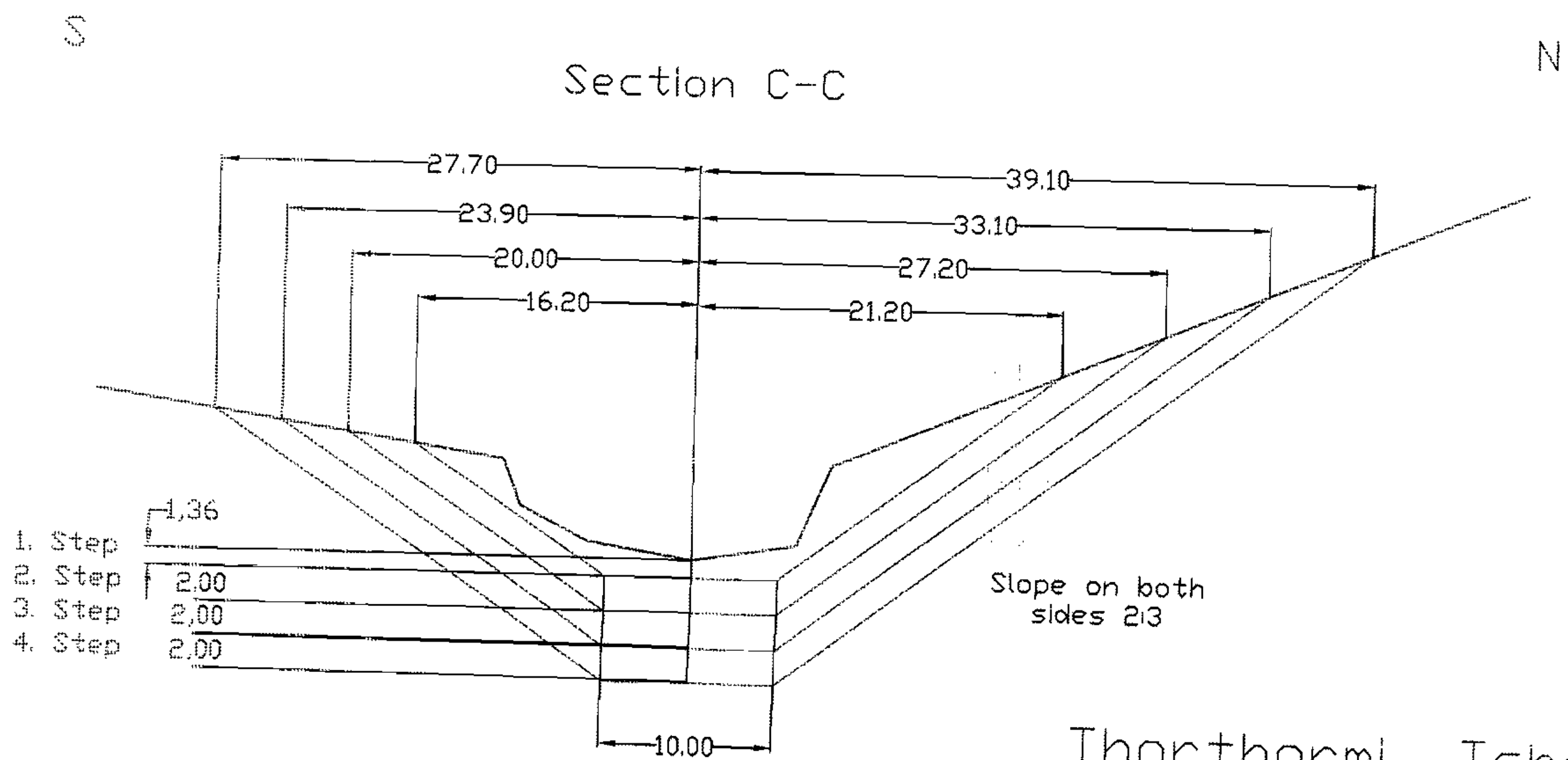
Measurement units in m



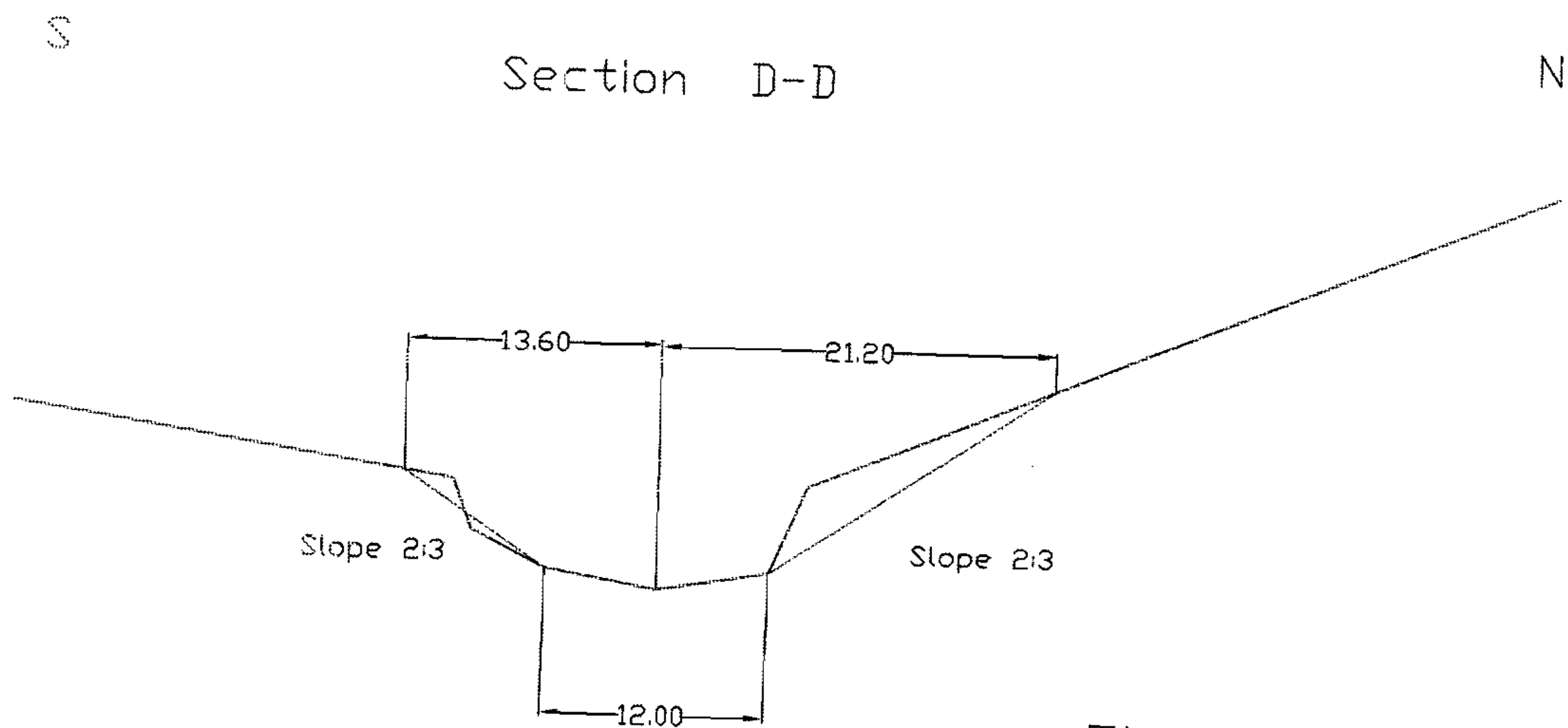
Thorthormi Tsho
Spillway channel
Cross section A-A
Construction plan 3
Scale 1:400
Measurement units in m



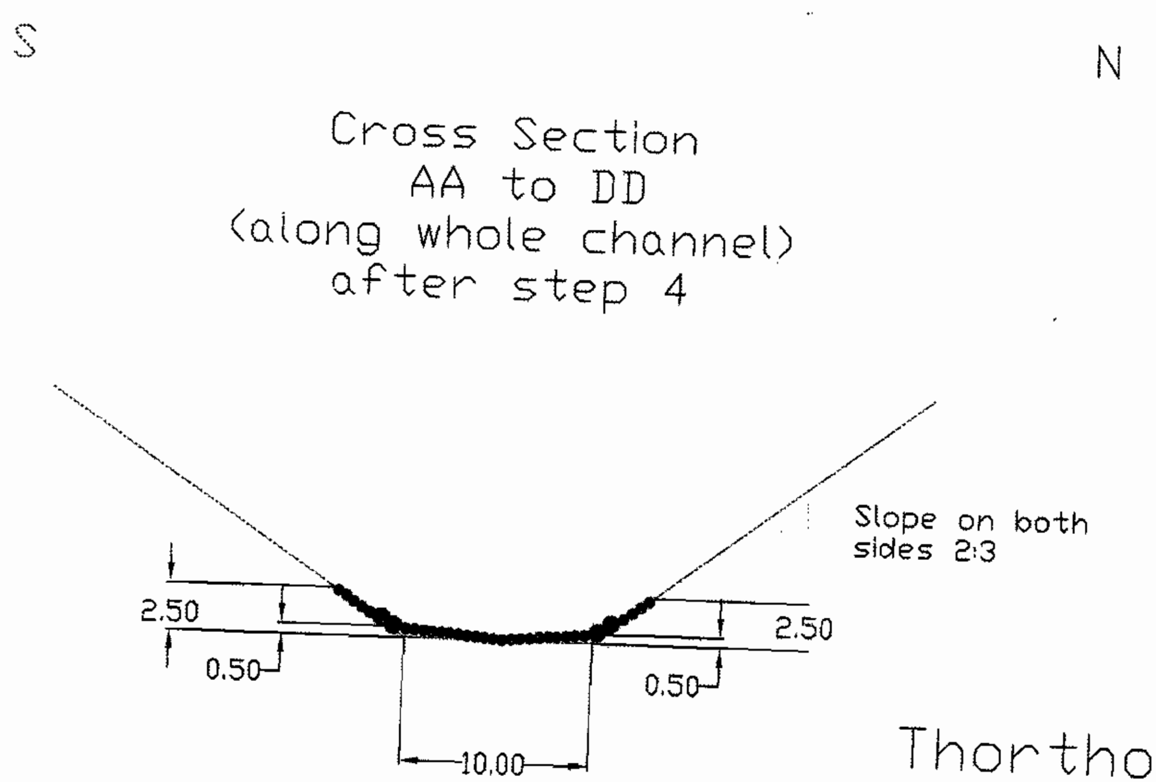
Thorthormi Tsho
Spillway channel
Cross section B-B
Construction plan 4
Scale 1:400
Measurement units



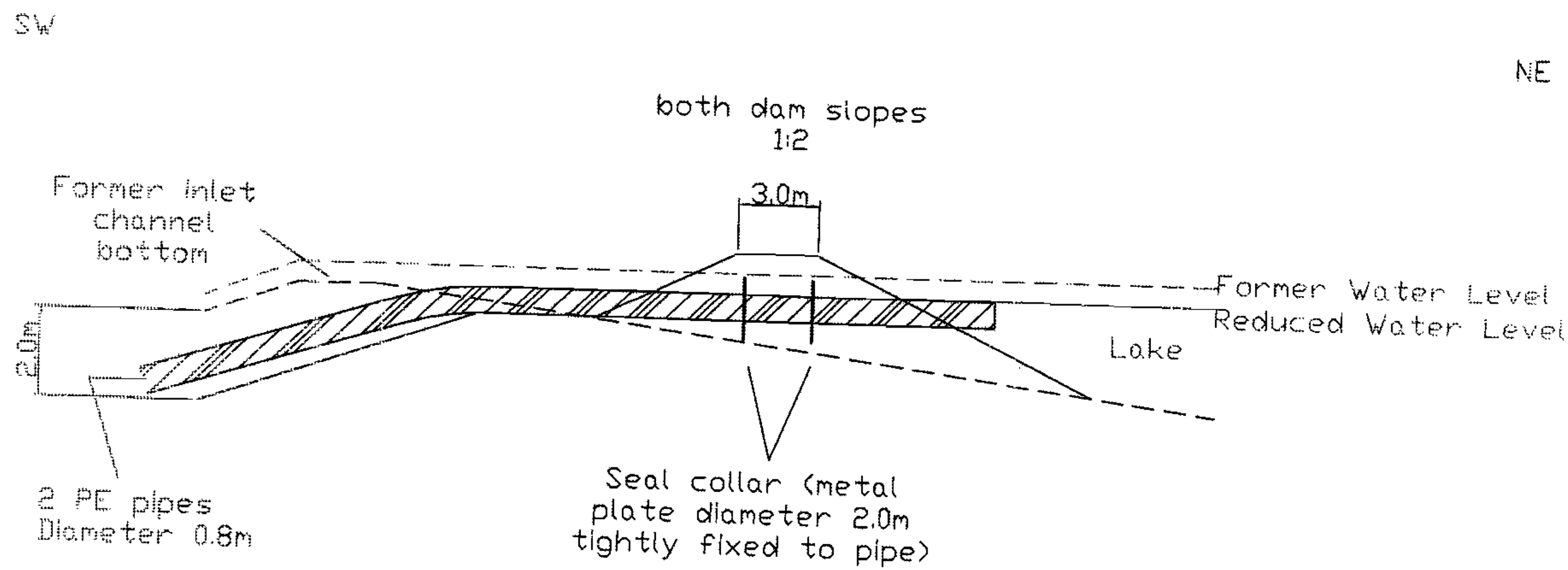
Thorthormi Tsho
Spillway channel
Cross section C-C
Construction plan 5
Scale 1:400
Measurement units in m



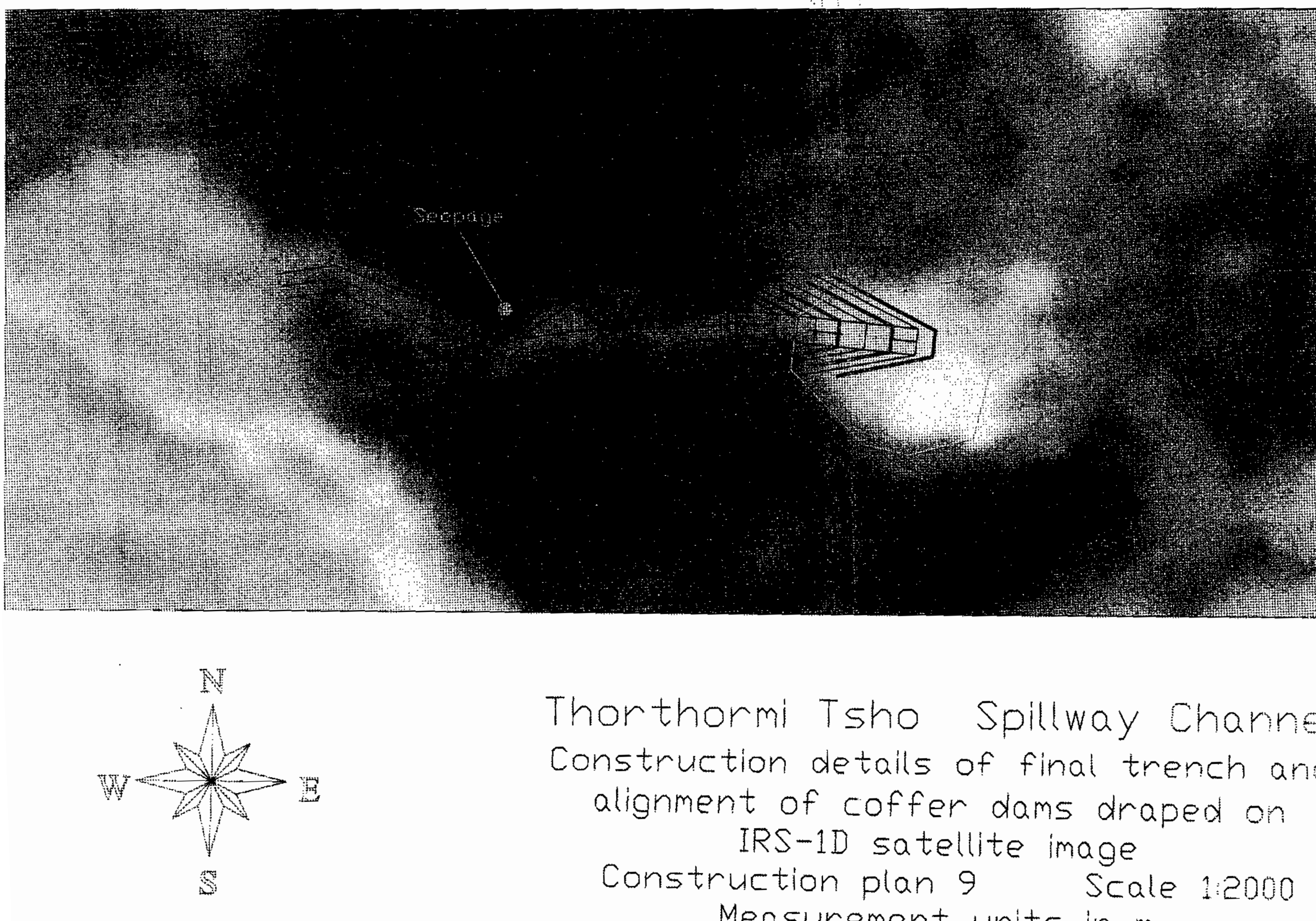
Thorthormi Tsho
Spillway channel
Cross section D-D
Construction plan 6
Scale 1:400
Measurement units in m



Thorthormi Tsho
Spillway channel
Armouring layer
Cross section
Construction plan 7
Scale 1:400
Measurement



Thorthormi Tsho
Spillway channel
Coffer dam
Construction plan 8
Scale 1:250
Measurement unit- ...



Thorthormi Tsho Spillway Channel
Construction details of final trench and alignment of coffer dams draped on IRS-1D satellite image
Construction plan 9 Scale 1:2000
Measurement units in m