CHAPTER 5 TAILINGS MANAGEMENT FACILITY

Knight Piesold Limited (KP) was commissioned by Mitsubishi Materials Natural Resources Development Corp.(mrc) to undertake a site selection study and a pre-feasibility design for a tailings management facility (TMF) in the Yanqul area in Oman from April to December 2001.

5-1 Site Selection

The sites were initially selected taking into account the topography of the area, environmentally sensitive areas and the position of the disposal area in relation to the process plant. The four -alternative schemes identified as being possible options for the TMF is shown in Fig. III-5-1.

5-1-1 Ranking System

A ranking system has been developed to appraise each option based on the following principal criteria:

- environmental impact
- water management(diversion structures)
- geology/geotechnical
- embankment works(volumes)
- topography(basin preparation and liner)
- location(with respect to process plant)
- ease of future expansion
- closure

The ranking system used in the assessment is to give the best site in each category a value of 1, the second best 2 and so forth.

The results of the ranking are as follows:

Option 1	20 points
Option 2	18 points
Option 3	14 points
Option 4	24 points

Based on the principal criteria of the ranking system, Option 3 is selected as the best solution.

5-1-2 Comparative Cost Estimate

An estimate of embankment costs and liner costs was prepared for the four options selected. The embankment and liner are the two major cost components of a tailings facility. Other costs such as decants and tailings delivery for the selected sites are not expected to show as much variation between the various options.

Option 3 has the lowest estimated cost.

The results of comparative cost estimates are as follows:

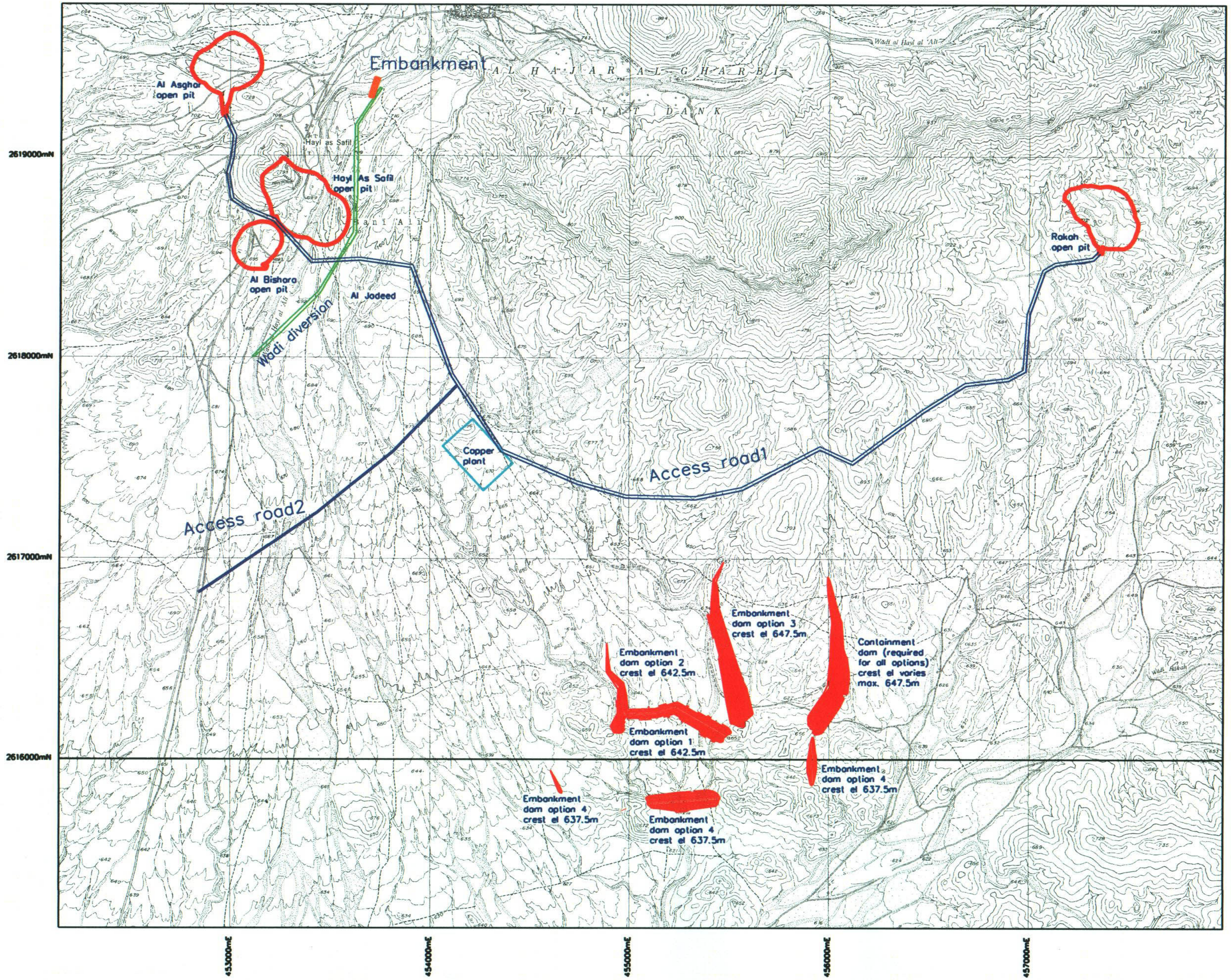


Fig.Ⅲ-5-1 Project location

Option 1	150%
Option 2	140%
Option 3	100%
Option 4	180%

In case of cost estimate of Option 3 regards as 100%.

Based on both the ranking criteria and capital costs, Option 3 is the preferred site for tailings disposal. Therefore Option 3 is selected for a pre-feasibility design.

5-2 Pre-Feasibility Design

Two tailings deposition methods were selected for comparison in this study.

- "Wet" tailings deposition, consisting of thickened tailings, pumped as slurry at a pulp density of 45% to 55%. (See Fig. III-5-2)
- "Dry" tailings deposition, at a moisture content of approx.10% to 15%, which will be transported by truck to the depository. (See Fig. III-5-3)

The main works for this study are summarized as follows:

- preliminary design of the main cost items for both "Dry" and "Wet" TMF options
- evaluation for the two tailings disposal options with respect to the environmental impact, capital and operating costs.

The Pre-feasibility design study includes:

- geotechnical investigation at the selected TMF site
- laboratory testwork on selected soil samples
- geotechnocal testwork on representative samples of tailings produced from laboratory bench-scale tests
- preliminary design of TMF and service infrastructure for the two selected tailings disposal options
- capital, operating and closure cost estimates for the two options

5-2-1 Design Parameters

The average rate of mining (or the mill treating rate) has been set at 3,000 tonnes/day which with 5% to concentrate results in a tailings production rate of 2,850 tonnes/day.

Tailings dry densities for design calculations were determined as follows:

Stability calculations	1.8 t/m^3
Wet tailings water balance volume calculations	1.4 t/m^3
Dry tailings water balance volume calculations	1.7 t/m^3

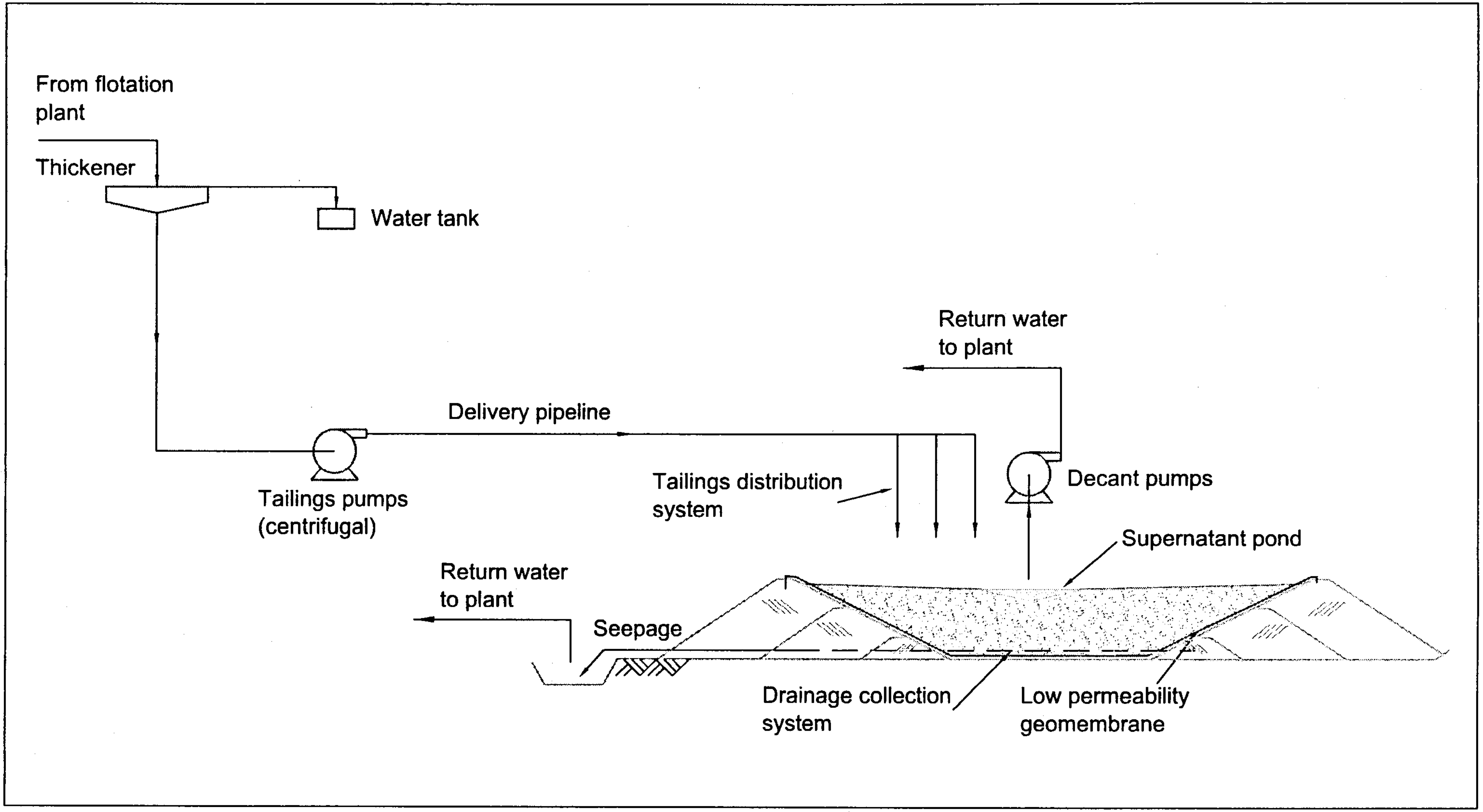


Fig.Ⅲ-5-2 Material handling schematic (wet tailings disposal option)

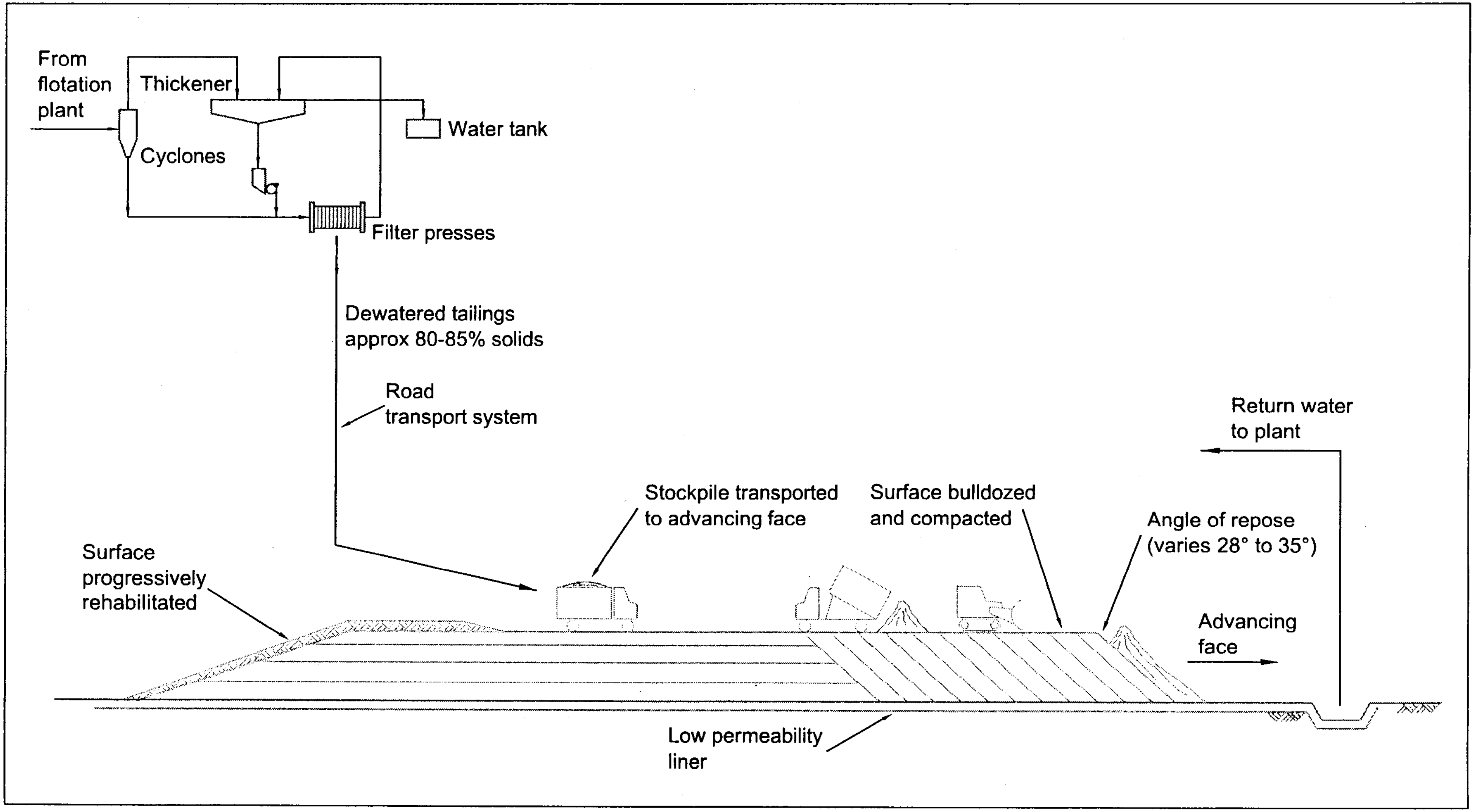


Fig.Ⅲ-5-3　Material handling schematic (dry tailings disposal option)

5-2-2 Geotechnical Investigation

A geotechnical investigation of the TMF basin was conducted in 2001,comprising 5 small diameter boreholes, drilled to a depth of 25m below ground surface and 12 trial pits excavated to an average depth of 1.5m below ground surface (refer Figs.III-5-4 to III-5-6, TableIII-5-1).

Natural materials for construction of the TMF earthfill embankments are to be predominantly sourced from within the basin of the TMF. However, certain materials such as the granular drainage materials and rockfill may have to be sourced from borrow areas located outside of the TMF area.

5-2-3 Tailings Characterisation Testwork

The tailings characterization tests are the followings:

- index testing including Atterberg limits and specific gravity analysis
- grading analysis including an hydrometer analysis of the finer fraction
- permeability test
- one-dimensional consolidation test
- undrained triaxial shear test
- undrained and drained settling tests
- air drying test

5-2-4 Slope Stability

The preliminary design of the tailings facility considers both scenarios("Wet" and "Dry") of tailings disposal.

The design was carried out in accordance with International Standards and considered stability under both static and dynamic loading conditions.

(1) Geotechnical design parameters

- Dry Tailings Disposal Option:

  Lower bound tailings material parameters

unit weight (kN/m^3)	18
angle of shearing resistance(degrees)	28

  Upper bound tailings material parameters

unit weight(kN/m^3)	18
angle of shearing resistance(degrees)	31

- Wet Tailings Disposal Option:

  Selected earthfill material parameters

unit weight(kN/m^3)	19
angle of shearing resistance(degrees)	30

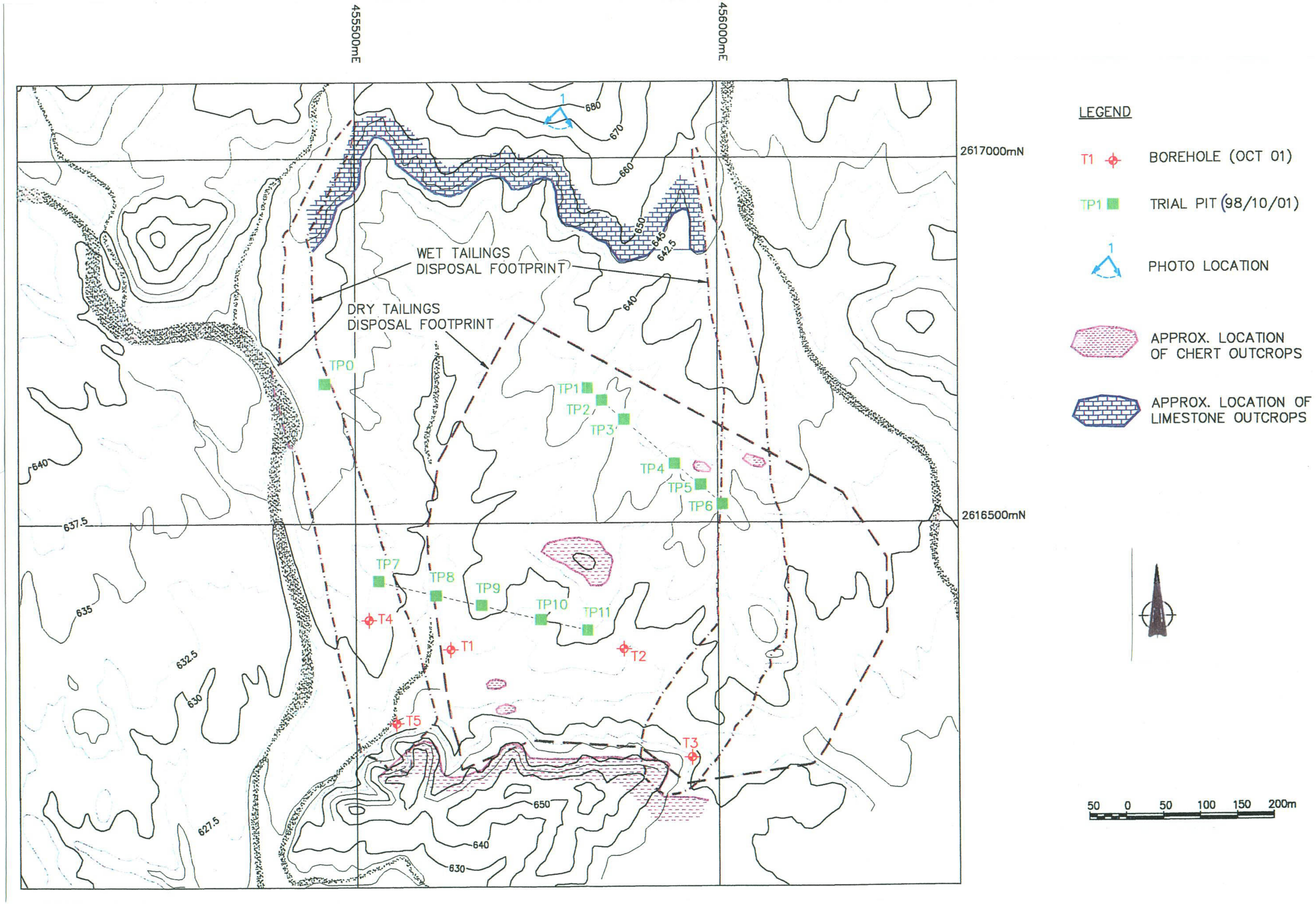


Fig.Ⅲ-5-4 Site investigation works

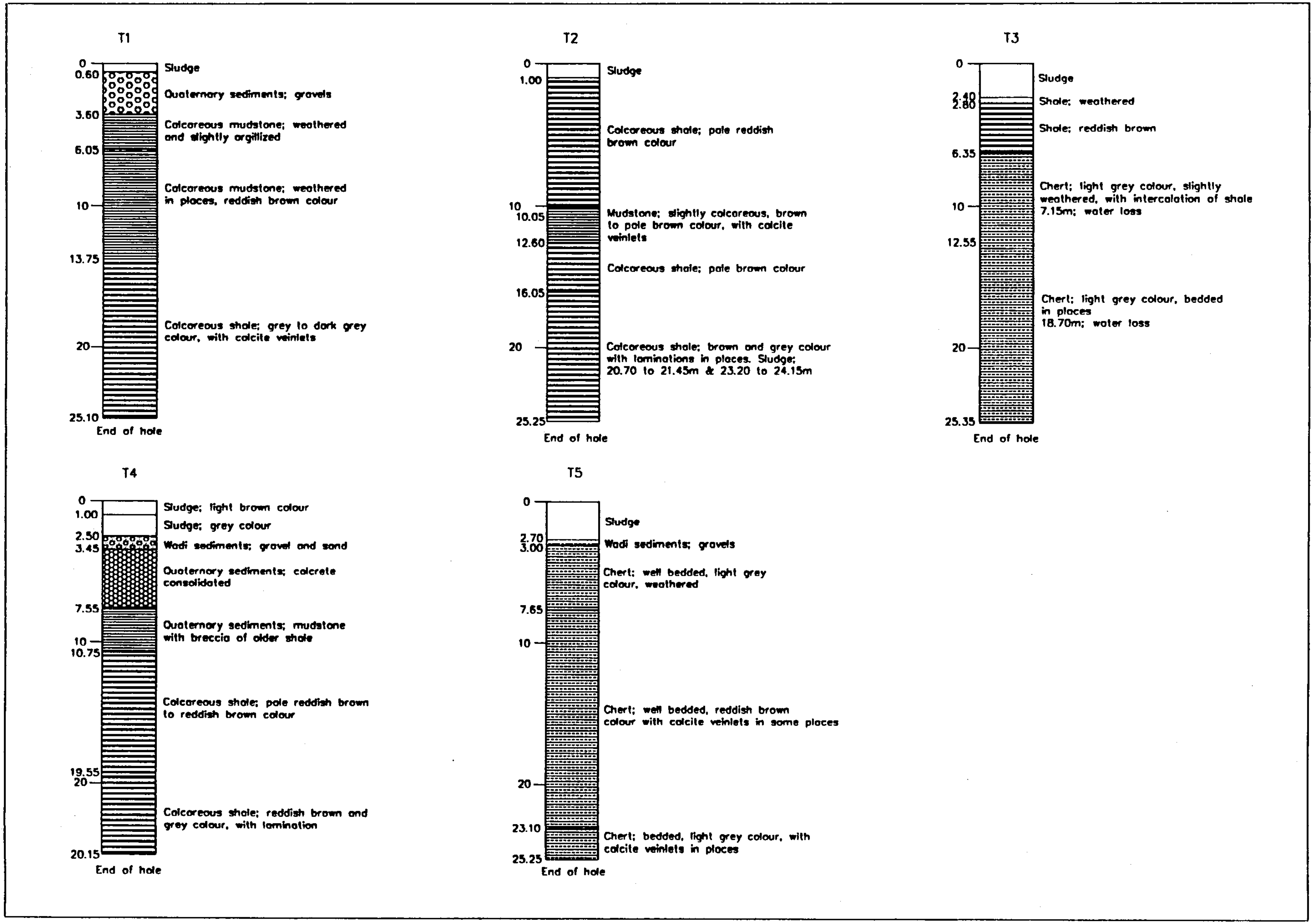


Fig.Ⅲ-5-5 Borehole logs

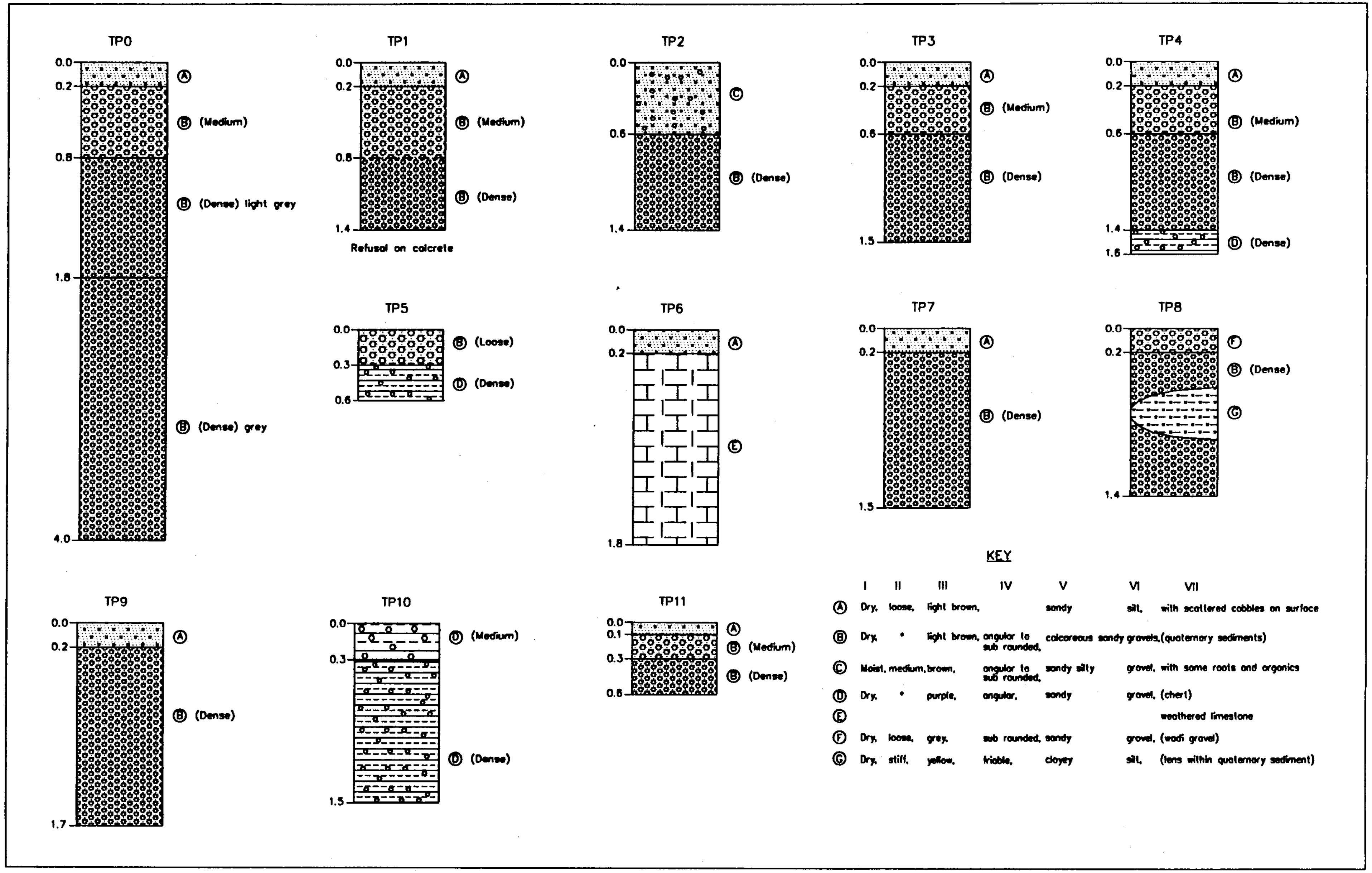


Fig.Ⅲ-5-6 Trial pit logs

Table Ⅲ-5-1 Geotechnical test results

Sample number	Borehole name	Depth (m)	Rock type	Apparent specific gravity			Moisture content (%)	Effective porosity (%)	Water content (%)	Unconfined compressive strength	
				Natural	Wet	Dry				Compressive strength (MN/m^2)	Modulus of deformation (MN/m^2)
1	MJOY-T1	8.80	Calcareous shale; weathered	2.522	2.574	2.468	4.29	10.59	2.19	25.20	24100
2	MJOY-T1	17.30	Calcareous shale	2.700	2.717	2.686	1.16	3.12	0.53	7.35	2160
3	MJOY-T1	17.40	Calcareous shale	2.660	2.693	2.636	2.15	5.66	0.91	11.30	16500
4	MJOY-T1	18.60	Calcareous shale	2.528	2.580	2.471	4.40	10.88	2.31	12.60	4820
6	MJOY-T2	16.30	Calcareous shale	2.482	2.543	2.409	5.55	13.37	3.02	16.10	3180
7	MJOY-T3	6.40	Chert	2.589	2.601	2.560	1.62	4.13	1.15	37.20	14900
8	MJOY-T3	10.60	Chert	2.606	2.616	2.578	1.46	3.77	1.08	14.90	33700
9	MJOY-T3	14.30	Chert	2.604	2.612	2.573	1.54	3.96	1.21	45.10	15800
10	MJOY-T3	23.70	Chert	2.597	2.612	2.576	1.37	3.54	0.81	37.20	25800
11	MJOY-T4	5.70	Calcreto	2.335	2.436	2.267	7.45	16.88	2.99	13.40	3270
12	MJOY-T4	7.10	Calcreto	2.222	2.369	2.159	9.68	20.91	2.88	8.73	3730
14	MJOY-T5	10.50	Chert	2.649	2.655	2.622	1.26	3.30	1.03	67.60	31700
15	MJOY-T5	16.40	Chert	2.638	2.648	2.621	1.05	2.76	0.65	18.00	22600
16	MJOY-T5	20.90	Chert	2.641	2.649	2.618	1.16	3.04	0.87	47.90	15900
17	MJOY-T5	23.90	Chert	2.629	2.634	2.623	0.42	1.09	0.24	40.40	17500

(2) Stability analysises

Preliminary stability analyses have been carried out for both tailings deposition scenarios.

The analysises have been based on the sections corresponding to the final embankment and heap design height. Intermediate stage heights have also been analysed, details of which are in Fig. III-5-7, Fig. III-5-8 and Fig. III-5-9.

For the seismicity for this study, the lower and upper values of the peak ground acceleration (PGA), i.e.0.08g and 0.24g under Operating Base Earthquake (OBE) conditions, have been considered to examine the sensitivity for the design to variation in PGA.

The results of the analyses for both tailings deposition scenarios are shown in Table III-5-2.

The results indicate that the design factors of safety for the wet tailings disposal option are achieved for both static and seismic loading conditions. In the case of the dry disposal option, the required factors of safety are satisfied except under high OBE loading conditions which represent a worst case scenario.

However, given the adoption of conservative values for the tailings material properties and the assumed high OBE loading conditions, the design section is therefore considered adequate for this conceptual design level. During detailed design, all criteria will be reviewed to ensure that the minimum design factors of safety are achieved.

It should be noted that significant additional laboratory testing and design analyses will be required during the detailed design phase to confirm these initial parameters and for optimisation of the design.

5-2-5 TMF Water Balance

Water balance modeling of the TMF was undertaken for dry and wet tailings disposal options to provide an estimate of the quantity of make-up water required and also to provide parameters for the design of pumps and pipelines.

The parameters and assumptions utilized for each water balance are provided with the out put of each water balance model.

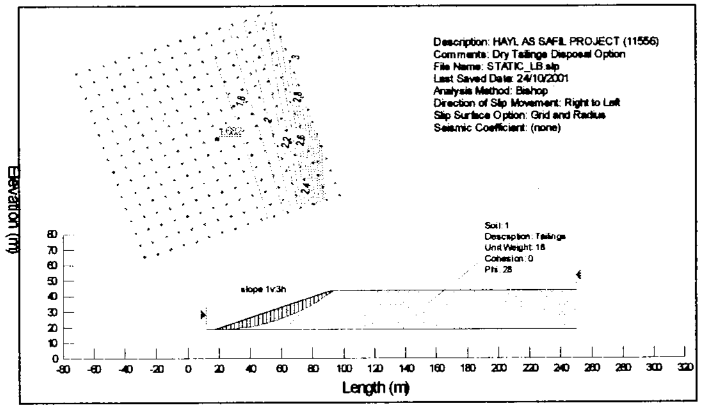
(1) The key factors

For the wet tailings option, three rainfall scenarios(dry, average & wet) were modeled to determine the sensitivity of the water balance. The three scenarios were based on recorded data from the rainfall stations at Rakah and other three stations.

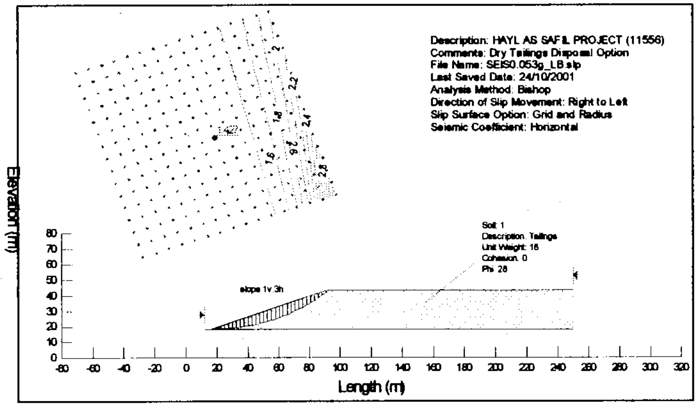
A value of 5.7mm per day of evaporation is given.

For a wet tailings disposal system with a liner, there will effectively be no loss due to seepage. Water collected by the underdrainage system will be pumped back to the facility and is not a loss to the system.

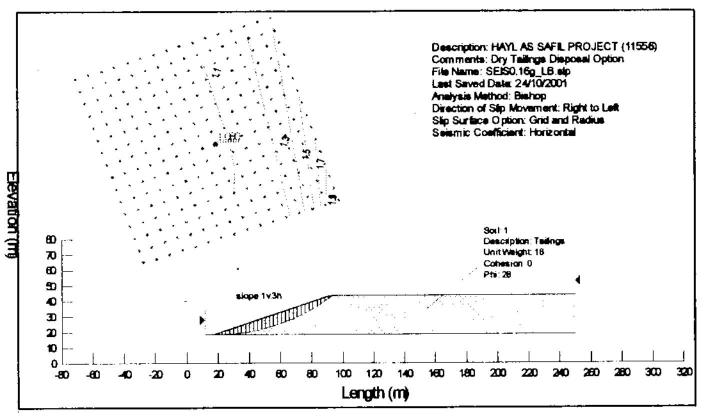
For the dry tailings disposal, it was assumed that whatever free water is available in the tailings will evaporate and is effectively lost to the system.



Final Deposition Height - Computed Critical Slip Surface and Minimum Factor of Safety for Static Loading Conditions



Final Deposition Height - Computed Critical Slip Surface and Minimum Factor of Safety for OBE (PGA = 0.08g) Loading Conditions



Final Deposition Height - Computed Critical Slip Surface and Minimum Factor of Safety for OBE (PGA = 0.24g) Loading Conditions

Table 1. Factor of safety summary for final and intermediate heights of dry deposition (lower bound tailings material parameters)

Deposition Height	Factor of Safety: Static loading	OBE (PGA = 0.08g) loading	OBE (PGA = 0.24g) loading
Final	1.682	1.427	1.080
2/3 of Final	1.735	1.467	1.105
1/3 of Final	1.847	1.552	1.159

Lower Bound Tailings Material Parameters

cohesion = 0 kN/m^2

effective angle of shearing resistance = 28 degrees

unit weight = 18 kN/m^3

Notes

1. Modelling Software

Analysis carried out using SLOPE/W Version 4.23 limit equilibrium model

2. Section

Cases presented have been based on the sections corresponding to the final embankment and heap design height. The factors of safety for intermediate stages are included in Table 1.

3. Loading Conditions

(i) Static Condition

(ii) Operating Basis Earthquake (OBE): PGA =0.08g

(iii) Operating Basis Earthquake (OBE): PGA =0.24g

4. Design Factors of Safety

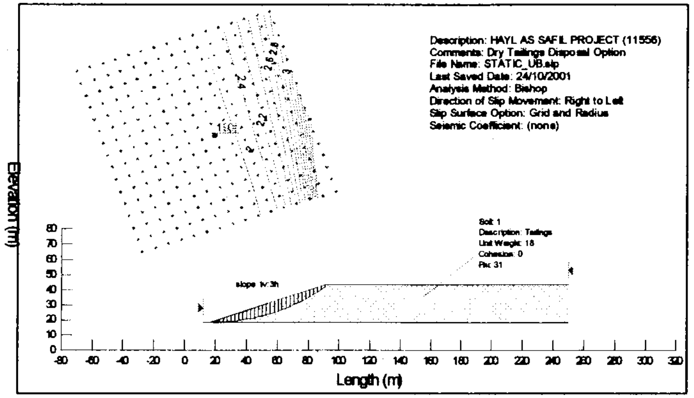
Static - 1.5

OBE - 1.25

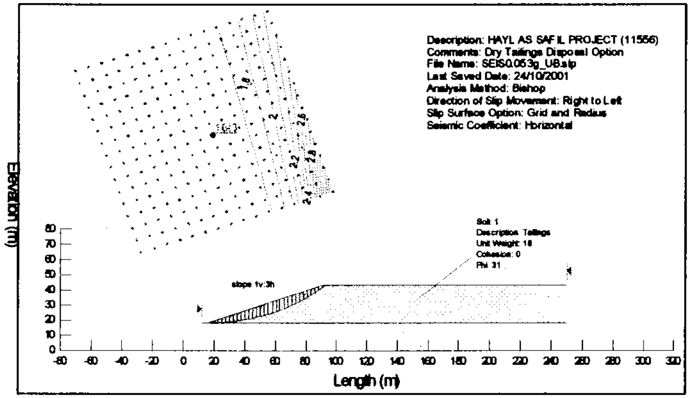
5. Pore Water Pressure Conditions

For both the dry and wet tailings disposal options it has been assumed that there will be no development of excess pore water pressure within the analysed slopes.

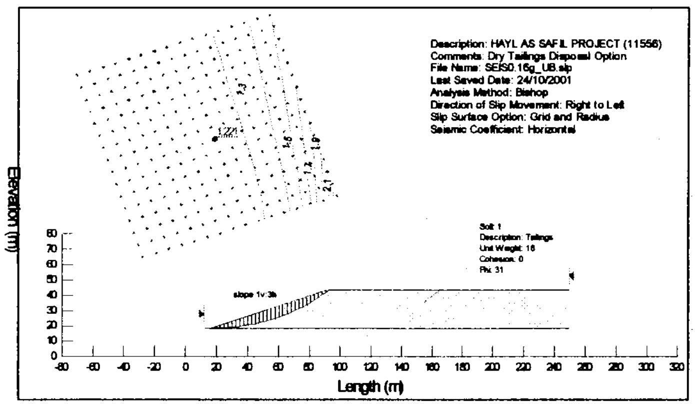
Fig. Ⅲ-5-7 Slope stability analysis results of lower bound material parameters.



Final Deposition Height - Computed Critical Slip Surface and Minimum Factor of Safety for Static Loading Conditions



Final Deposition Height - Computed Critical Slip Surface and Minimum Factor of Safety for OBE (PGA = 0.08g) Loading Conditions



Final Deposition Height - Computed Critical Slip Surface and Minimum Factor of Safety for OBE (PGA = 0.24g) Loading Conditions

Table 2. Factor of safety summary for final and intermediate heights of dry deposition (upper bound tailings material parameters)

Deposition Height	Factor of Safety		
	Static loading	OBE (PGA = 0.08g) loading	OBE (PGA = 0.24g) loading
Final	1.901	1.613	1.221
2/3 of Final	1.959	1.658	1.249
1/3 of Final	2.083	1.748	1.305

Upper Bound Tailings Material Parameters

cohesion = 0 kN/m^2

effective angle of shearing resistance = 31 degrees

unit weight = 18 kN/m^3

Notes

1. Modelling Software

Analysis carried out using SLOPE/W Version 4.23 limit equilibrium model

2. Section

Cases presented have been based on the sections corresponding to the final embankment and heap design height. The factors of safety for intermediate stages are included in Table2.

3. Loading Conditions

(i) Static Condition

(ii) Operating Basis Earthquake (OBE): PGA =0.08g

(iii) Operating Basis Earthquake (OBE): PGA =0.24g

4. Design Factors of Safety

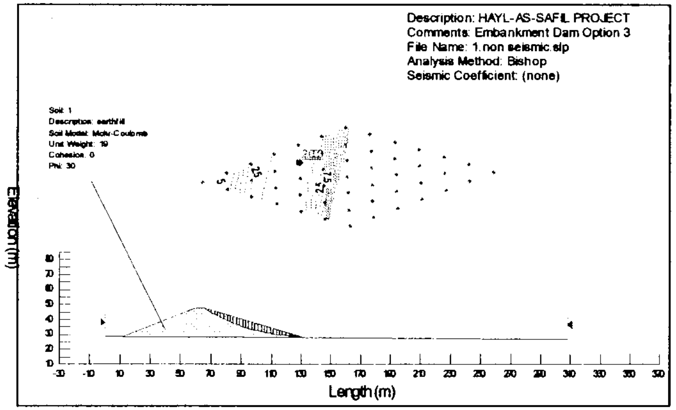
Static - 1.5

OBE - 1.25

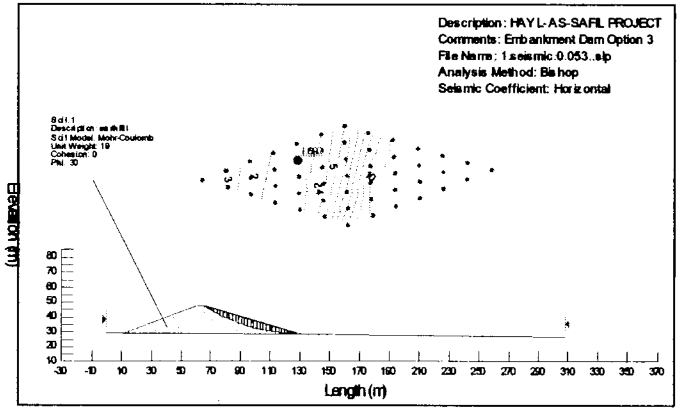
5. Pore Water Pressure Conditions

For both the dry and wet tailings disposal options it has t assumed that there will be no development of excess po water pressure within the analysed slopes.

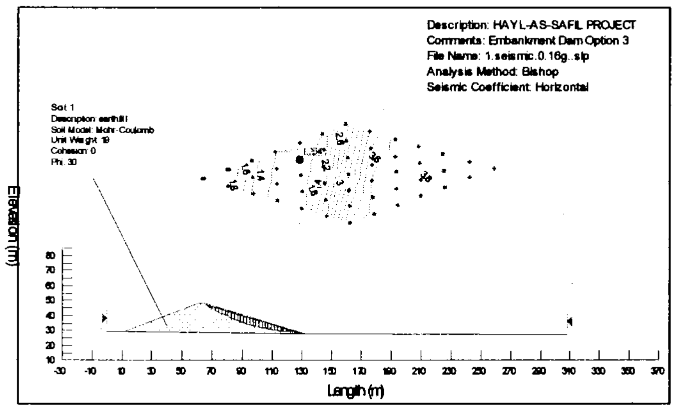
Fig. Ⅲ-5-8 Slope stability analysis results of upper bound material parameters.



Final Embankment Height - Computed Critical Slip Surface and Minimum Factor of Safety for Static Loading Conditions



Final Embankment Height - Computed Critical Slip Surface and Minimum Factor of Safety for OBE (PGA = 0.08g) Loading Conditions



Final Embankment Height - Computed Critical Slip Surface and Minimum Factor of Safety for OBE (PGA = 0.24g) Loading Conditions

Table 3. Factor of safety summary for final and intermediate embankment heights (selected earthfill material parameters)

	Factor of Safety		
Embankment Height	**Static loading**	**OBE (PGA = 0.08g) loading**	**OBE (PGA = 0.24g) loading**
Final	2.023	1.690	1.254
Stage 3	2.042	1.710	1.273
Stage 2	2.054	1.721	1.283
Stage 1	2.160	1.793	1.321

Selected Earthfill Material Parameters

cohesion = 0 kN/m²

effective angle of shearing resistance = 30 degrees

unit weight = 19 kN/m³

Notes

1. Modelling Software

Analysis carried out using SLOPE/W Version 4.23 limit equilibrium model

2. Section

Cases presented have been based on the sections corresponding to the final embankment and heap design height. The factors of safety for intermediate stages are included in Table 3.

3. Loading Conditions

(i) Static Condition

(ii) Operating Basis Earthquake (OBE): PGA =0.08g

(iii) Operating Basis Earthquake (OBE): PGA =0.24g

4. Design Factors of Safety

Static - 1.5

OBE - 1.25

5. Pore Water Pressure Conditions

For both the dry and wet tailings disposal options it has been assumed that there will be no development of excess pore water pressure within the analysed slopes.

Fig. III-5-9 Slope stability analysis results of selected material parameters.

Table Ⅲ-5-2 Stability analysis results

	Dry Tailings Disposal - Stability of Tailings Heap		Wet Tailings Disposal – Stability of Earthfill Dam	Minimum Required Design FoS
Loading Conditions	FoS for Lower Bound Material Parameters	FoS for Upper Bound Material Parameters	FoS for Selected Material Parameters	
Static	1.7	1.9	2.0	1.5
OBE (PGA=0.08 g)	1.4	1.6	1.7	1.25
OBE (PGA=0.24 g)	1.1	1.2	1.25	1.25

FoS = factor of safety

Table Ⅲ-5-3 Summary of total capital, operating, maintenance and closure costs

Dry Tailings Disposal				
Description	**Cost ($ over 8 years)**			
	0.5	1	1.5	3
Capital cost	8 391 781	8 391 781	8 391 781	8 391 781
Operations and maintenance	12 425 766	12 829 531	13 233 297	14 444 594
Closure	3 000 000	3 000 000	3 000 000	3 000 000
Total	**23 817 547**	**24 221 312**	**24 625 078**	**25 836 375**
Less residual value on filter press (35%)	- 889 000	- 889 000	- 889 000	- 889 000
Total (inc. residual value)	**22 928 547**	**23 332 312**	**23 736 078**	**24 947 375**
Wet Tailings Disposal				
Description	**Cost ($ over 8 years)**			
	0.5	1	1.5	3
Capital cost	9 801 423	9 801 423	9 801 423	9 801 423
Operations and maintenance	5 924 088	7 318 995	8 713 901	12 898 621
Closure	5 700 000	5 700 000	5 700 000	5 700 000
Total	**21 425 511**	**22 820 418**	**24 215 324**	**28 400 044**
Ratio of dry over wet lifetime costs	107.00%	102.20%	98.00%	87.80%

(2) Water Tailings Disposal

The water balance for precipitation in dry years shows that 92% of the water in the tailings slurry will be lost to evaporation and storage in the tailings voids.

The average quantity of water available from the tailings facility during a wet year is 31,460m^3 per month.

(3) Dry Tailings Disposal

The result from the water balance indicate that all water contained within the tailings is lost to the system.

5-2-6 Construction Works

(1) Embankment Construction

The construction of embankment for the wet tailing option and embankment zone for the dry tailings option would commence with stripping of upper soil horizon and stockpiling this material in designated areas outside the basin footprint. Excavation would continue until a competent foundation. Fill for the embankments would be sourced from within the basin area and placed in layers and compacted.

On completion of the fill, the slopes would be trimmed and the cushion layer for the liner placed where required.

(2) Basal Lining Systems

Clay for possible use as a lining material at Wadi Kabir Dam and at Al Dahara would not achieved the required permeability without processing. Therefore for the purposes of this study, a depository lined with HDPE (1.5mm thick minimum) is technically suitable and is likely to prove the most economic option.

After excavation for embankment construction, a layer of fine material will be placed in a 300mm cushion layer on which to place the liner.

Material for the cushion layer, filters and gravel drains may not be readily available in the site.

It is expected that processing of wadi gravels close to the site will be the most economical option.

(3) Basal Drainage System

For the wet disposal option, a network of drains will be provided in the basin below and above the HDPE basal lining system.

For the dry disposal option, a basal drainage system is not required because of the lack of free water in the system.

(4) Diversions and Run-Off Control

For the dry tailings option, an unlined diversion channel will be constructed to intercept clean run-off from the catchment outside of the TMF and divert the flow to the wadis to the east and west.

For the wet tailings option, the external catchment area is small and no clean run-off diversion will be provided. However, a channel will be provided along the tailings pipeline access that will intercept tailings in the event of a pipe break and divert this flow into the TMF.

(5) Spillway

For the dry tailings option, no spillways are required.

For the wet tailings option, a permanent spillway will be provided as part of closure.During operations, sufficient freeboard will be provided to retain any storms.

5-2-7 Operations and Maintenance

(1) Tailings Management System

Dry tailings disposal option:

The cake dewatered in a filter press will be transported to the depository from the process plant.

The heaped material will be spread and compacted by a bulldozer in controlled layers, to achieve optimum in situ density.

Tailings surfaces on reaching final level will be graded and compacted to ensure optimum drainage conditions provided for closure.

Wet tailings disposal option:

Tailings slurry will be pumped to the depository in a permanent HDPE pipeline.

HDPE moveable tailings distribution pipes will be placed along the crests of the confining embankments, from where the tailings will be discharge into the depository via a number of spigots.The management of the deposition system will be planned to allow maximum time for deposited tailings to settle and desiccate.

(2) Return Water System

Dry tailings disposal option:

No return water pumping system has been provided and, when required, water which may have accumulated in the drainage collection ponds will be collected by tanker truck and used for suppressing dust in the facility or returned to the plant for re-use.

Wet tailings disposal option:

The return water system will consist of a submersible pump on a floating pontoon, supplying an HDPE return water pipeline.

(3) Maintenance

The degree of maintenance required on embankments should be minimal, however, a regular check should be made of the following points.

- seepage or damp patches at the toe
- cracks on the face of the dam
- erosion of the face of the dam

· blockage or deterioration of the surface drainage or underdrainage

These checks should be carried out daily.

(4) Monitoring

In addition to regular visual inspection of embankments and associated works, routin monitoring by instruments is also required to check on performance.

Piezometers will be provided where there is a need to measure pore water pressure within embankments and the tailings mass.

Survey beacons will be installed on the embankments so that a periodic check may be kept on the physical movement of the embankments.

Regular in situ density measurements should be undertaken on deposited tailings to confirm the design parameters and the components of the storage facility.

The TMF shold be survey annually in order to confirm the capacity of the facility.

5-2-8 Closure Strategy

On completion of working, the TMF is to be engineered for dry closure such that the surface of the deposited tailings is rapidly made stable and potential for wind and water erosion minimized in line with the objectives of providing for long-term stability and an appropriate end use requiring minimal maintenance. The process of closure will commence prior to the cessation of mining, and will continue as the performance of the depository demands.

The major cost of closure is capping of the TMF. Typical capping systems consist of a low permeability barrier, drainage layer and soil cover. In arid climates, the potential for revegetation is limited and erosion protection of the upper soil cover needs to be considered.

The final system can only be selected after further study and site work, however, for this study a preliminary capping system has been selected consisting of HDPE geomembrance, sand/gravel drainage, soil cover and erosion protection.

5-3 Capital, Operational And Closure Costs

(1) Capital Costs

A cost estimate for both the wet and dry tailings options was prepared.

The estimated capital cost for constructing a wet tailings disposal facility is $9,801,423,which is approximately 17% higher than the $8,391,781 cost for a dry tailings disposal facility. The main items, which create this cost difference, are that wet tailings deposition requires :

- a large embankment construction
- a large geomembrance lined area
- basal drainage system
- a tailings delivery and return water system

The dry tailings disposal option has the high capital cost of the filterpress, which makes up 36% of the capital cost.

The capital costs include a contingency allowance of 15% and EPCM of 12%.

(2) Operational and Closure Costs

Operational costs over the lifetime of the project including the cost of water, based on a supply cost of 0.5,1,1.5 and 3 Baisa per Imperial gallon, have been calculated as the range of $12,425,766 to $14,444,594 for the dry tailings disposal option, compared with the range of $5,924,088 to $12,898,621 for the wet tailings disposal option. (See Table III-5-3).

The costs for closure have been calculated as $5,700,000 for the wet tailings disposal option and $3,000,000 for the dry tailings.

(3) Total Lifetime Costs

The combined total for the capital, operating and closure costs indicates that for low water costs, the wet tailings disposal option has the lowest lifetime cost and that for high water costs, the dry tailings disposal option has the lowest lifetime cost,

In terms of the expected accuracy of the cost estimate, the total life costs for the two disposal options are not significantly different and other factors need to be considered in making a decision as to which is the preferable option. One of these factors is environmental risk.

5-4 Conclusions

Both options have been designed to minimize the impact on the environment, however, the impact on the environment of contamination in the case of an extreme event. Based on risk analysis and experience, the wet tailings disposal method generally has a higher potential impact than the dry tailings for the same set of circumstances.

In view of the potential impact on the environment and a risk of water cost, "Dry " tailings disposal option will be adopted for this study.