International Journal of Mining Science and Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Overburden management in open pits: options and limits in large limestone quarries

Claudio Oggeri [a,*], Taddeo Maria Fenoglio [a], Alberto Godio [a], Raffaele Vinai [b]

[a] Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Torino 10129, Italy
[b] College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter EX4 4QF, United Kingdom

ARTICLE INFO

Article history:
Received 18 January 2018
Received in revised form 9 March 2018
Accepted 10 May 2018
Available online xxxx

Keywords:
Open pit
Overburden
Soil testing
Limestone quarry
Muck
On-site testing

ABSTRACT

The management of overburden is an important task in open pit exploitations. Site topography and morphology as well as geological and geotechnical properties of natural and remoulded materials are the most important factors affecting the disposal phase. Economic and environmental requirements must be followed in order to achieve the best reclamation results, keeping into account site constraints such as slope stability, hauling and dumping issues, and interactions with groundwater. This paper deals with the above mentioned issues, illustrating a rational approach applied on the case of a large limestone quarry where the thickness of the overburden is relevant and the spoil material has to be dumped in a flooded pit. The proposed multidisciplinary approach led to the selection of most suitable methods for excavation, transportation and disposal. The selection was based on a detailed laboratory and site characterisation that defined favorable and adverse factors to be considered during the preliminary study of a large quarrying project.

1. Introduction

Overburden handling has important impacts on surface mining projects and has to be carefully planned considering both mining activities and site rehabilitation [1,2]. Overburden handling activities start at the beginning of the mining project, when a huge amount of material from initial underground development or stripping is removed for site preparation [3,4]. Overburden removal and disposal activities usually take place at the same time with quarrying. The amount of removed overburden and its excavation rate are related to (1) the required ore productivity, (2) the morphology and geometry of the ore deposit (Fig. 1) and (3) the effectiveness of onsite or offsite disposal processes, which in principle should be the most cost-effective and technically sound method.

Over 90% of the mining activities in developed countries adopt open pit methods [5]. In large open pits, the orebody is usually found relatively close to the surface (thus ensuring overburden–to–ore ratios suitable for profitable mining operations) in sub-horizontal or slightly inclined deposits. In the case of top mountain exploitation, other challenging conditions are encountered both during overburden removal and consequent filling. Top mountain coal stripping is nowadays still operated in some countries, although environmental constraints, as huge volumes of materials are removed and reshaped, and the technical problems require a careful planning and detailed monitoring and controls.

Overburden materials can be soil, soft and hard rock. A wide range of equipment can be utilised for overburden removal in open-cast mining, according to the ground type and the topographic context.

If the excavated material cannot be reprocessed (either for economic or technical reasons), overburden has to be disposed by means of a range of systems, typically combined with excavation techniques according to the overall productivity. The efficiency of each method depends mainly on dumping distance and site morphology. In flat and large locations, stripping is conveniently undertaken by fixed or semi-mobile systems (such as bucket wheel, chain bucket or draglines and belt conveyor), which delivers large production but have low flexibility [6].

The selection of methods for overburden removal and disposal in open pit mining involves geotechnical, topographical and typical site aspects, as resumed in Table 1 [3,7–10]. Fig. 2 represents also a summary for equipment selection.

During the removal phase, the following aspects are involved:

(1) Geotechnical features: material characteristics (presence of jointed/fractured formations, grain size distribution, moisture content, plasticity indices, ground strength and bearing

* Corresponding author.
E-mail address: claudio.oggeri@polito.it (C. Oggeri).

https://doi.org/10.1016/j.ijmst.2018.06.011
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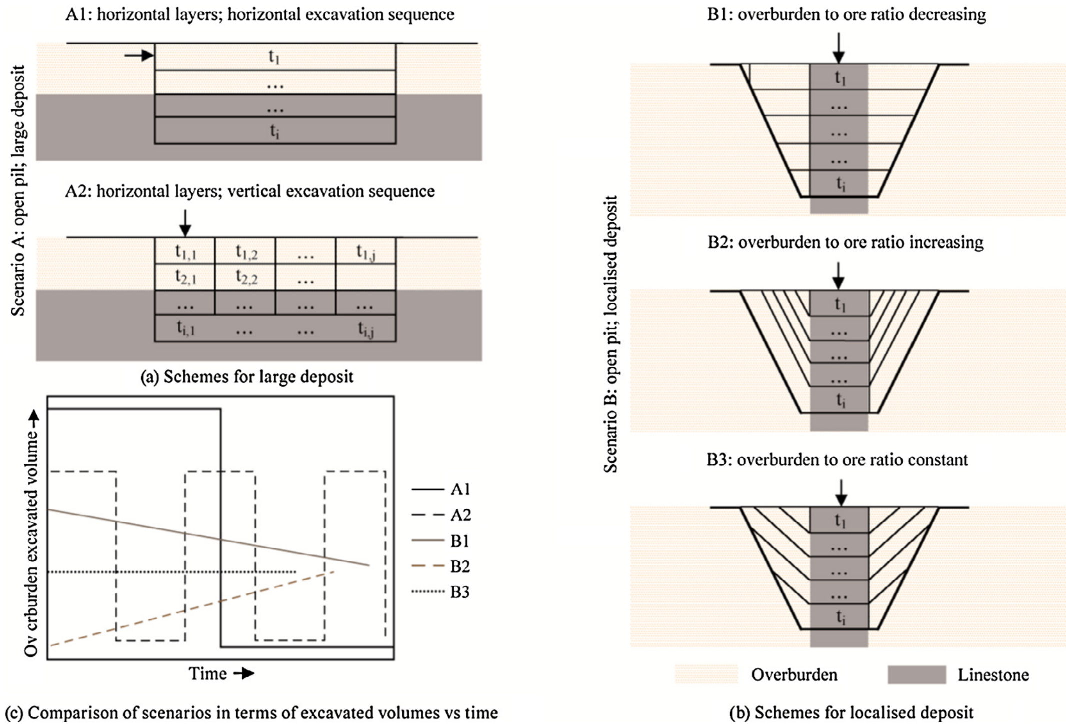

Fig. 1. Rate of overburden excavated volume as a function of quarry configuration.

capacity that is compatibility with plant-site installations and site means); and stability of natural and excavated slopes (rock falls, landslides, and mud flows);

(2) Environmental features: groundwater interaction (variations in groundwater table, depletion of aquifers, chemical pollution such as fuels, greases, acid drainage, etc.); air pollution (gases such as hydrocarbons, CO, NO, etc., air-borne dusts such as silica, asbestos and noise); and land (weathering, surface runoff such as flooding, waterlogging, erosion, etc., vibrations, plants and wildlife, landscape appearance);

(3) Logistic features: climatic conditions (heavy rainfalls/snowfalls, access available by seasonal conditions); site topography/morphology (gradients, distances, and terrain); and accessibility (primary/secondary roads, ramps, and railroads); availability of energy (supply of fuel, electric power, and water).

During the disposal phase, the following aspects are involved:

(1) Geotechnical features: material characteristics (grain size distribution, moisture content, compaction in natural or induced, deformability); groundwater interaction (pore pressure, filtering, piping); settlements (short and long term); and stability (rock falls, landslides, mud flows, subsidence);

(2) Environmental features: groundwater interaction (variations in natural drainage such as flooding and waterlogging, chemical pollution such as metals, sulphates, etc., increasing turbidity); air pollution (gases such as hydrocarbons, CO, NO, etc., air-borne dusts such as silica and asbestos, noise); land (weathering, surface runoff such as flooding, waterlogging, erosion, etc., chemical pollution such as solid waste buried, plants and wildlife, landscape appearance);

(3) Logistic features: climatic conditions (heavy rainfalls/snowfalls, access available by seasonal conditions); site topography/morphology (gradients, distances, terrain); accessibility (primary/secondary roads, ramps, railroads, reuse after site rehabilitation); and availability of energy (supply of fuel, electric power, water).

From the geotechnical point of view, mechanical and hydraulic properties of the encountered materials are key factors during both removal and disposal operations, affecting fundamental aspects such as ground strength, bearing capacity and stability [11,12]. Muck management is a critical phase also in other engineering sector, such as tunnelling, due to its environmental and geotechnical implications. Reuse versus disposal of excavated material represents a recurrent dilemma also from the economical point of view [13,14]. Moisture content and stickiness of soils can cause clogging of the excavation equipment, affecting their efficiency [15,16]. Mining operations often result in waste tailings containing a certain amount of clay fraction, which can affect the spoil consolidation behavior. The assessment of consolidation properties is therefore required for understanding the behavior of slurry ponds and/or slurry backfilling [17].

Overburden disposal is one of the principal environmental concern for mining industry, both in case of surface stockpiles as well as in case of in-pit disposal [3,18,19].

The control of the interaction of disposed material with water, which could lead to interference with surface water as well as groundwater, both in terms of water table variations and contamination by leachates and heavy metals, is of paramount importance [5,19,20].

Choices on plant installations and adopted equipment are affected by local constraints such as climatic conditions, site topography or morphology, accessibility and availability of energy [3].

All the above mentioned aspects need to be carefully considered from the preliminary design stage of large mining projects. The optimisation of the process arises from the evaluation of technical, economic, and environmental interrelated factors. Although each case presents its own specific requirements and problems, a general methodology can (and must) be derived. A conceptual and

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Table 1
Overburden removal and disposal methods related to ground type.

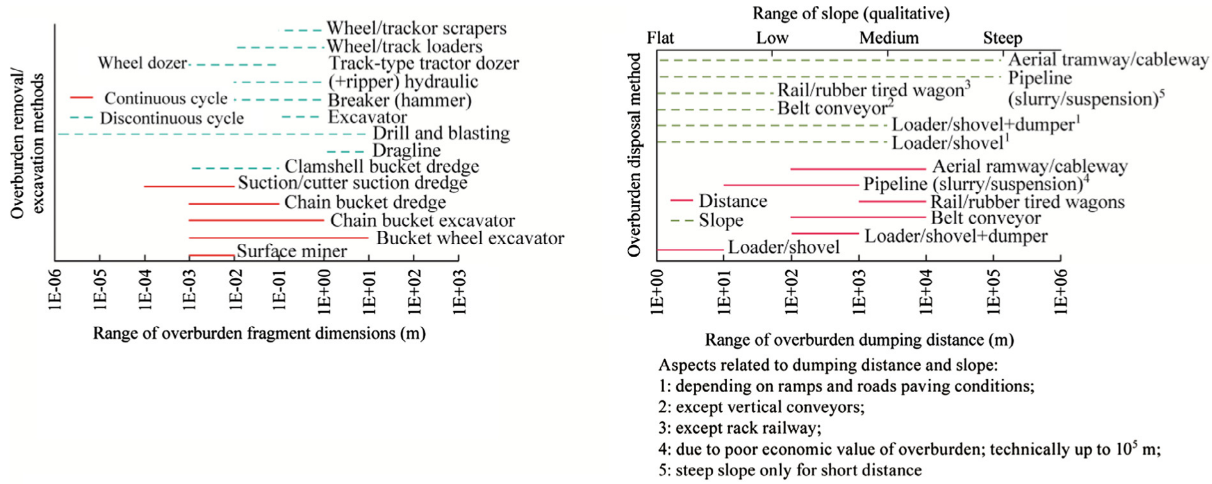
(a) Overburden removal methods related to ground type

		Overburden ground type			Groundwater	Topographic context*			Equipment for overburden disposal**					
		Soil	Hard soil/soft rock	Hard rock	Capability of working under water table	Flat (lowlands)	Low to moderate slope (hills)	Moderate to steep slope (mountains)	Machine itself[1]	Dumper	Belt conveyor	Rail/ rubber-tired wagon	Pipeline (slurry/ suspension)	Aerial tramway/ cable way
Overburden removal/ excavation method in open pits	Continuous cycle		Surface miner		No	Yes	No	No	No	Yes	Yes	No	No	Yes
		Bucket wheel excavator			No	Yes	No	No	No	No	Yes	Yes	No	Yes
		Chain bucket excavator			No	Yes	No	No	No	No	Yes	Yes	No	Yes
		Chain bucket dredge			Yes	Yes	No	No	No	No	Yes	Yes	Yes	No
		Suction/cutter suction dredge			Yes	Yes	No	No	No	No	Yes	Yes	Yes	No
	Discontinuous cycle	Clamshell bucket dredge			Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	No
		Dragline			No	Yes	No	No	Yes	No	Yes	Yes	No	No
		Drill and blasting			No	Yes	Yes	Yes	–	Yes	Yes	Yes	No	Yes
		Excavator			Yes (on pontoon)	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes
			Hydraulic breaker (hammer)		No	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes
		Track-type tractor – dozer (+ ripper)			No	Yes	Yes	Yes	Yes	No	No	No	No	No
		Wheel dozers			No	Yes	Yes	No	Yes	No	No	No	No	No
		Wheel or track loaders			No	Yes	Yes	Yes	Yes	Yes	No	No	No	No
		Wheel-tractor scrapers			No	Yes	Yes	No	Yes	No	No	No	No	No

(b) Overburden disposal methods related to ground type

	Overburden ground type		
	Soil	Hard soil/soft rock	Hard rock
Overburden disposal method in open pits	Efficiency depending on moisture content (stickiness/ adhesion)	On-site crusher to reduce oversize fragments if necessary	On-site crusher to reduce oversize fragments if necessary Wear and abrasivity issues
	Loader/shovel (eventually suitable also for dumping within short distance)		
	Efficiency depending on moisture content (stickiness/ adhesion)	On-site crusher to reduce oversize fragments if necessary	On-site crusher to reduce oversize fragments if necessary; Wear and abrasivity issues
	Loader/shovel+dumper		
	Not suitable for high moisture content	On-site crusher to modify grain size distribution	On-site crusher to modify grain size distribution Not suitable for abrasive materials
	belt conveyor		
	Depending on moisture content	On-site crusher to reduce oversize fragments if necessary	On-site crusher to reduce oversize fragments if necessary
	Rail/rubber-tired wagons		
	Clog up risk (stickiness/adhesion)	Only for fine-crushed materials Clog up risk (sedimentation)	Only for fine-crushed materials Not suitable for abrasive materials Clog up risk (sedimentation)
	Pipeline (slurry/suspension)		
	Depending on moisture content	On-site crusher to reduce oversize fragment if necessary	On-site crusher to reduce oversize fragment if necessary
	Aerial tramway/cable way		

* Typical topographic context in which the machine is adopted.
** Suitable equipment for inpit and/or expit overburden disposal associated to excavation method; and 1 is as a function of hauling and dumping distance.



(a) Range of dimensions of overburden fragments vs. overburden removal/excavation methods

(b) Range of suitable dumping distance and slope vs. overburden disposal methods

Fig. 2. Types of equipment used depending on the geometrical size of rock elements and topographical local conditions.

rational approach requires on-site and laboratory tests, as well as site monitoring, numerical modelling and back analysis, carried out by a multidisciplinary team (mining engineer, environmental engineer, geophysicist, and material engineer).

This paper describes the adoption of such approach on a relevant case history, showing how the multidisciplinary contribution can represent a way for a proved solution, based on scientifically sound results.

2. Methods of investigation

2.1. Site description

The analysis focuses on a specific case of a large limestone quarry, located in Gaurain-Ramecroix district in the Wallonne Region, North-West of Belgium, which was chosen as relevant example for addressing the importance of a comprehensive approach in the overburden management. In the study area, limestone deposits are covered by several metres of clay and sand overburden. As shown in the geological cross section (Fig. 3), limestone deposit consists of sub horizontal or slightly inclined layers with thickness ranging from 10 to 20 m.

As per the results of explorative drillings, the optimum rock composition (determined as 45% of CaO content by the quarry owner) can be found in the first metres close to the surface and at about 90 m deep. Open pit quarrying is planned following the orientation of geological layers, starting with an initial opening from the surface (60 m ASL), until the deepest low-quicklime content layer at 250 m BSL. The exploitation requires the removal and disposal of about 50 million cubic metres (Mm^3) of overburden material during the 20-year quarry lifespan. Limestone deposit is covered by a 50–70 m thick layer of soil–clayey sand and clay–which has to be removed by means of excavators/shovels and chain bucket excavator.

Material must then be disposed in a nearby exhausted multiple-bench open pit partially flooded, with groundwater level expected to raise in the next years (see Fig. 4). The designed productivity has been fixed at 1000 tons/h by the quarry owners. The following options have been considered as disposal strategies: (a) surface hauling and dumping technique; (b) dumping from fixed discharge points located on top benches by means of conveyor belt system, (c) dumping in the flooded sector of the pit from floating belt conveyors type pontoon or (d) dumping on quarry pit banks with

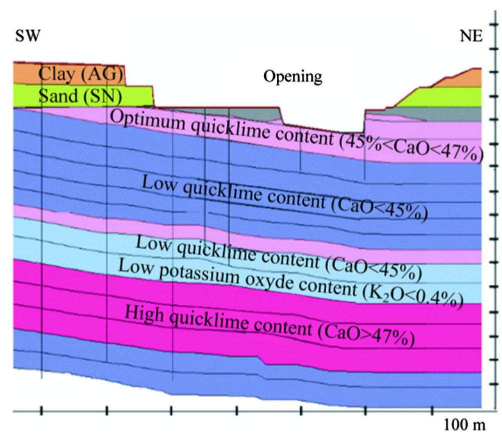


Fig. 3. Geological cross section of the limestone deposit.

(a) Chain bucket excavator operating onsite, front view

(b) Chain bucket excavator in operation in silty soil, lateral view

(c) Exhausted quarry pit in which the overburden has to be disposed

Fig. 4. Meaningful details of overburden during excavation and open pit at the end of exploitation phases.

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conveyor belt system then spreading the material in the form of slurry, using suction dredges. The following main issues have been outlined: (1) geological preliminary investigations and geomechanical characterization of overburden materials are required in order to evaluate an effective disposal state, (2) the consistency of the excavated overburden material, which results in big sticky lumps, influences the choice of the correct hauling and dumping method; and (3) the pit where excavated material is to be disposed is partially flooded by groundwater and the water level will raise over the years, therefore fine particles behavior in terms of solid concentration in water and long-term metal and sulphates release is to be assessed.

Outcomes of the research activities related to point (1) are discussed in this paper, while results and discussion on issues identified in points (2) and (3) will be presented in detail in two other dedicated papers.

2.2. Geomechanical tests

Several tests have been carried out both at the Soil Mechanics Laboratory of Politecnico di Torino and on-site, in order to assess geomechanical properties of overburden materials, as summarized in Table 2.

Oedometer tests were performed as these can simulate laterally confined material settling under increasing vertical load steps. This stress configuration could be considered similar to the conditions of backfilling material during hauling and dumping operations. Oedometric load steps are therefore representative of the contribution of additional layers of dumped material into the quarry pit, since material will settle over the years preferentially in vertical direction, because of the lateral confinement action applied by boundary pit rock walls.

Oedometric modulus was obtained for each load step and hydraulic conductivity and was calculated as following:

$$M = \frac{\delta \sigma'_v}{\delta \varepsilon_v} \tag{1}$$

$$K = \frac{C_V,\ \gamma_w}{M} \tag{2}$$

where σ_v' is the vertical effective stress; ε_v the axial strain, C_v the coefficient of consolidation; and γ_w the unit weight of water.

Table 2
Laboratory and on-site tests.

Item	Test	Standard
Laboratory	Determination of density (unit weight)	ASTM D7263-09
	Determination of liquid limit, plastic limit, and plasticity index	ASTM D4318-10e1
	Determination of moisture content	ASTM D2216-10
	Determination of particle size distribution	ISO/TS 17892-4:2004
	Determination of shear strength	ASTM D5607-08
	Oedometer test	ISO/TS 17892-5:2004
	Sedimentation test	
	Soil classification (AASHTO)	ASTM D3282-15
	Soil classification (USCS)	ASTM D2487-11
	Soil slump test	
On-site	Cone penetration test (CPT)	ASTM D5778-12
	Determination of the California Bearing Ratio (CBR) using Dynamic cone penetrometer (DCP)	ASTM-D 6951-3
	Determination of density	ASTM D1556/D1556M-15e1
	Dump truck crossing test	
	Overburden dumping from quarry pit top benches	
	Plate load test (PLT)	EN 1997-2:2007

Direct shear tests were performed in order to evaluate mechanical parameters of soils such as angle of friction and cohesion. Those parameters, together with compaction and consistency, are required for determining the stability of overburden deposit. The interpretation of the results is based on Mohr-Coulomb failure criterion:

$$\tau = \sigma_v \cdot \tan(\varphi) + c \tag{3}$$

where τ is the shear strength; σ_v the vertical (confining) stress; and φ the angle of internal friction and c the intercept of the failure envelope or cohesion. For sandy soils a bi-linear failure envelope can be adopted for emphasizing the higher friction angle due to dilation effect for low confining vertical stress [21].

Consistency of geomaterials was evaluated through slump test, which, although not standardized for soils applications, was effectively used to investigate fine-grained soils plasticity and mine tailings consistency [9,22]. The interpretation of the test is based upon the measurement of the cone fall and rest angle of the overburden material (sand, clay and mixed materials), at different moisture contents. Slump test can give indications on soil consistency, material self-support capacity, soil plasticity and stickiness, helping in the technical evaluation of possible disposal.

2.3. Sedimentation tests

The study investigated the interference of the dumped material with the water of the exhaust quarry pit in terms of turbidity and sedimentation rate, as the water of the flooded pit is currently used by the cement production plant for its day-to-day activities. The sedimentation of different soil types was investigated following two main purposes: (a) to assess the sedimentation process when the overburden material is dumped into a quarry lake, evaluating solid particles concentration of the progressively clarified water near the surface, and (b) to provide data for the recirculation of water from the quarry lake to the plant for industrial use. The water/solid interaction is particularly critical when the adoption of reverse dredging system for overburden management (which involves the handling of the material in the form of slurry) is considered. The reverse dredging system modifies the consistency of the soil by crushing and remoulding it from a submerged stockpile of dumped material, then the slurry is pumped at the surface level along a pipeline and it is released under the water level (Fig. 5).

While a high degree of dispersion of soil particles is desired for the pumping stage, this affects negatively the sedimentation phase, as the finer the particles the longer the deposition time is. Slurry circulation along the pipeline requires the control of other parameters, particularly for avoiding sticky behavior or clogging of the systems. Settlement of particles has been discussed in the scientific literature in many studies. A novel approach for the determination of drag coefficient of spherical particles based on known theoretical laws and fitted using a large number of experimental data has been recently proposed [23]. In this research, sedimentation tests were performed following the settlements of a 1:3 soil/water turbid obtained through mechanical stirring, in two vertical cylinders, referred to as "small" (15 cm diameter, 50 cm height) and "big" (20 cm diameter, 100 cm height), and measuring the clarified water height over the time (Fig. 6).

2.4. On-site tests

On-site tests were carried out with the overburden material dumped without being compacted in a study area beside the planned disposal pit, in order to simulate the real scale condition of the barren soils once disposed after excavation. The study area was divided in three sub-areas, one for each overburden material

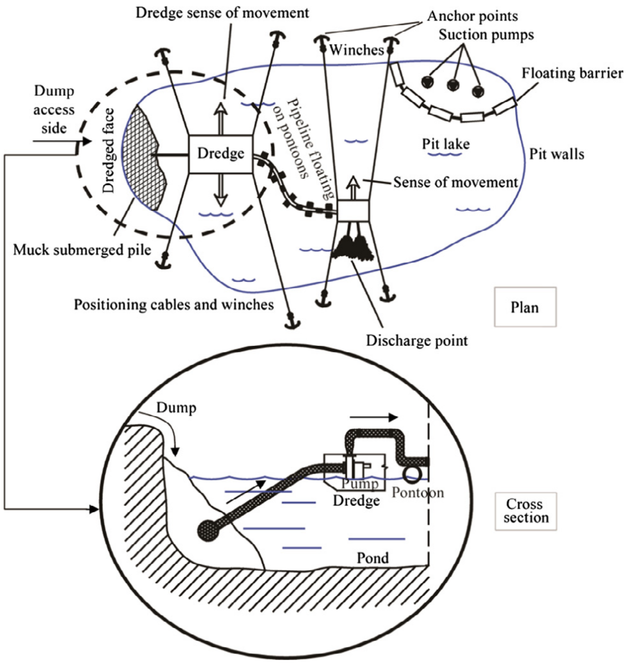

Fig. 5. Schematic plan and cross-section of the dredging system operating into quarry lake.

(sand, sand and clay mix and clay). Field tests were performed on each area obtaining a set of parameters for each material.

Cone penetration test (CPT) was carried out using a static penetrometer (Dutch cone), typically adopted for soft soils. The cone tip (60° angle and cross-sectional area of 10 cm^2) was pushed with a penetration rate of 2 cm/s, measuring the penetration resistance q_c every 20 cm of depth.

California Bearing Ratio Index evaluates the bearing capacity of natural grounds, by comparison with a standard granular soil (well-graded crushed stone). CBR index was indirectly obtained performing a dynamic cone penetrometer test (DCPT), according to the relationship proposed in the literature for fine grained soils [24–26]. The DCP test is carried out measuring the penetration depth of a cone tip (60° cone angle, 20 mm diameter) after each drop of a 8 kg mass hammer from an height of 575 mm. Penetration index (PI) is calculated as the ratio of depth and blow count and is then related to CBR with log-log equation in the following general form:

$$\log(CBR) = A - B \cdot [\log(PI)]^C \tag{4}$$

where A, B and C are regression constants.

Plate load test (PLT) is used to determine the ultimate bearing capacity of soils and consists in measuring the settlements of a steel plate placed on the ground under several vertical load steps. The deformation modulus M is measured from the slope of the load-settlement relationship, calculated as follows:

$$M = \frac{\Delta P}{\Delta S} \cdot D \tag{5}$$

where ΔP is the pressure on the plate at a defined load step; ΔS the settlement of the plate (average of 3 dial gauges readings); and D the diameter of the plate. The plate used for the test had a surface equal to 750 cm^2, whilst the vertical load was applied by means of hydraulic jacks using a dump truck as counter-action frame. Tests were successful only on sandy soil.

In-situ density was obtained using the sand-cone density apparatus. For each soil sample, in-place wet (ρ_w) and dry density (ρ_d) were calculated as follows:

$$\rho_w = \frac{M_w}{V} \tag{6}$$

$$\rho_d = \frac{M_d}{V} \tag{7}$$

where M_w and M_d are respectively the moist and dry mass of the tested material from the test hole; and V the volume of the test hole.

Obtained results from on-site tests on investigated soils are summarized in Table 3a and b.

A dump truck crossing test was designed *ad hoc* in order to investigate the mechanical behavior of the overburden materials at the real scale under operative conditions, as well as to estimate logistic issues concerning the productivity of available dumping equipment. A 50 m long embankment was built using overburden material at its natural moisture content, alternating sand, clay and mixed material. A three axles articulated dump truck with a gross weight of 53 tons was driven back and forth on the longitudinal cross section (Fig. 7). Observed interaction between the dump truck and the embankment was used as indicator at real size of the potential of overburden removal by surface hauling and dumping technique.

As noted in Fig. 7, in the upper part, longitudinal cross-section of the embankment and dump truck crossing test; in the lower part, the vehicles passages have been repeated until the guidance was possible, depending on compaction and moisture content of soil layers, simulating the cyclical operations of earthmovers above a real filling deposit, with the new embankment, on the left, and after several passages, in the center and on the right.

The disposal option of dumping from fixed discharge points located on top benches by means of conveyor belt system was simulated with a full scale test. In order to evaluate the actual slope

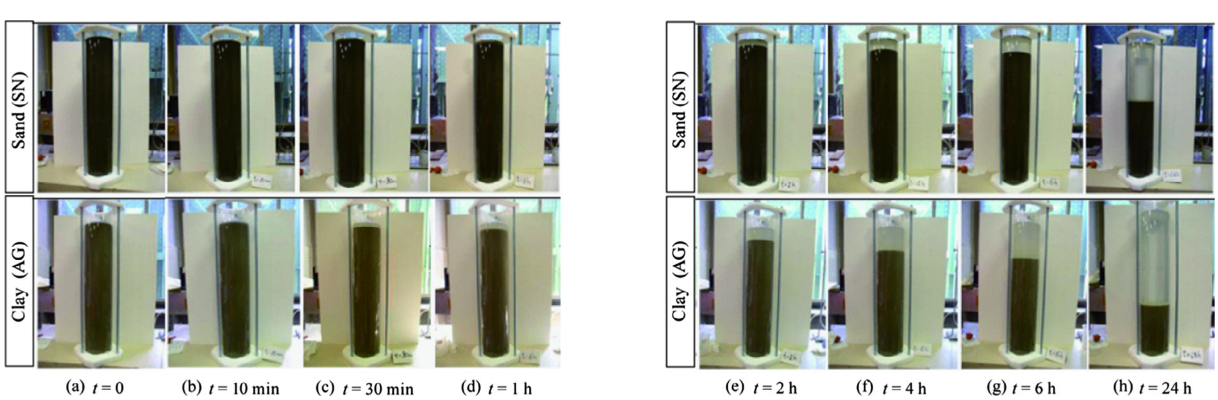

Fig. 6. Phases of 24 h sedimentation tests in a measuring cylinder (20 cm diameter, 100 cm height) for black sand (SN) and gray clay (AG).

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Table 3
Geotechnical characterization of overburden material in lab and on site.

(a) In lab

Material	Identification	Specific gravity (g/cm^3)	Moisture content (%)	Grain size distribution (%)			Consistency indices (%)			Classification		Angle of friction (peak) Φ_p (°)	Cohesion c (kPa)
				<2 µm*	<20 µm	<75 µm	LL	LP	IP	AASHTO	ASTM		
Clay	Grey clay (AG)	1.90–1.93	34.4	(45) 68	87	99.9	96	31	65	A-7-5 A-7-6	CH	20	67
	Brown clay	1.90–1.93	32.3	(38) 51	62	99.8	74	23	50	A-7-6	CH		
Sand	Black sand (SN)	1.87–1.92	17.1	22	28	46.0	42	23	18	A-7-6	SC	28	65

(b) Onsite

Cone penetration test			California bearing ratio			Plate load test			Density				
Test	Material	q_{cmax} (MPa)	Test	Material	CBR index	Test	Material	M (MPa)	Test	Material	ρ_w (g/cm^3)	w (%)	ρ_d (g/cm^3)
CPT1	sand	2.2	CBR1	sand	3.2–3.7	PLT1	Sand	9.69	D1	Sand	1.919	25.8	1.526
CPT2	sand+clay mix	1.4	CBR2	sand + clay mix	3.3–6.7	PLT2	Sand + clay mix	Not achievable	D2	Sand + clay mix	1.926	25.3	1.537
CPT3	clay	0.7	CBR3	clay	3.1–6.7	PLT3	Clay	Not achievable	D3	Clay	1.922	23.7	1.553

* The values <2 µm in brackets were obtained throughout Andreasen's pipette method (ISO 13317-2:2001).

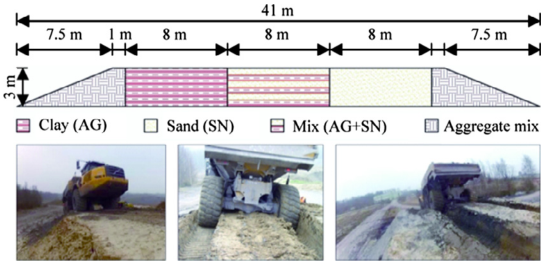

Fig. 7. Conditions for site testing of different dumped and compacted overburden materials.

angle of the material when progressively dumped in the pit from the top, a significant volume of overburden material was dumped by trucks with the aim of creating a stockpile along one of the benched wall of the quarry. The geometry of the slope generated by this test was measured through laser scanner survey, and the storage capacity of the pit under these conditions was estimated combining these results with the geotechnical properties of the dumped materials, repeating the simulation all along the quarry border, taking also into account the accessibility of the area.

3. Results

3.1. Geomechanical tests

Geotechnical characterisation indicated that the investigated clay has a high plasticity. Grey clay, which has 68% of particles finer than 2 µm (Fig. 8a), has a liquid limit over than 95% and a plasticity index of about 65%. Natural moisture content of clay exceeds plastic limit, which means that hauling and dumping operations will have to deal with a plastic and sticky material. Sand showed a lower liquid limit, which leads to a plasticity index lower than that of clay, being the plastic limit similar for the two materials.

Shear test results (Fig. 8b) allowed to estimate an internal friction angle for sand of 28° (failure envelope 2), which can be considered moderately low, due to the high content of fines. Shear test on clay resulted in an internal friction angle of 20°. The high content of fines in both materials can also explain the similar cohesion found for sand (about 65 kPa) and clay (about 68 kPa). A shear strength behavior typical for a cohesive material can be assumed for the two investigated soils.

Oedometric curves (Fig. 9) indicated a higher stiffness of the sand compared with clay, with a total vertical strain ratio between the two materials around 1:5.

At the maximum vertical confined stress of 1600 kPa, Oedometric modulus of sand and clay was about 90 and 15 MPa respectively, whereas the hydraulic conductivity was in the range of 10^{-9} m/s for the two materials (Fig. 9). Such very low values of hydraulic conductivity both for sand and clay are presumably due to the high content of fines, which can reduce the hydraulic conductivity by several order of magnitude [27].

Cone fall and rest angle from slump tests were measured versus the moisture content (Table 4). Equal cone fall was measured by sand having 20–25% less moisture content than clay (on average), indicating that clay kept a better consistency with high moisture levels. This is due to difference in consistency indexes, as clay has a wider plastic range, being its plasticity index (PI) more than three times the PI calculated for sand. Values of cone rest angle confirmed the same trend: both clay and sand reached the same maximum cone angle (about 80°), but moisture contents were about 30% and 60% for sand and clay respectively. The behavior of a mixed clay/sand material gave intermediate results, both in terms of cone fall and angle.

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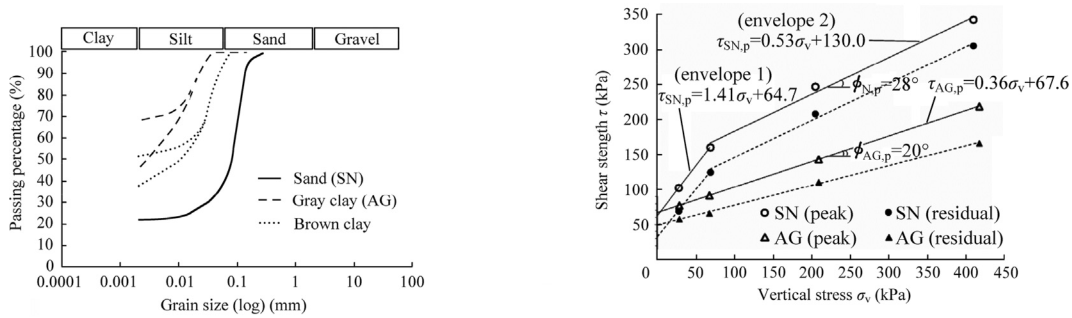
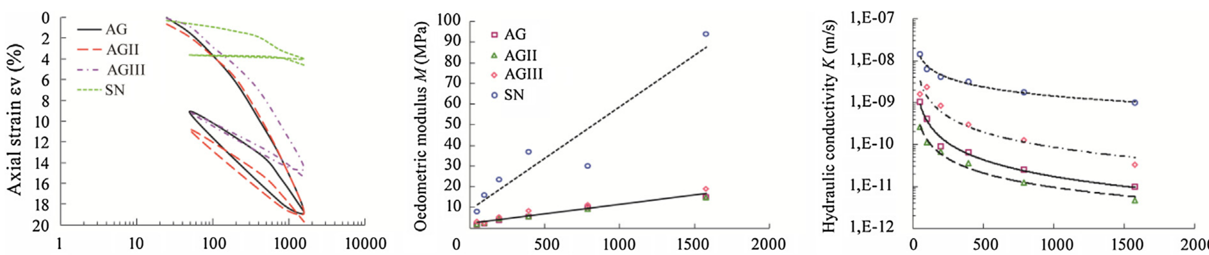


(a) Grain size distribution of the investigated soils

(b) Peak and residual shear strength from direct shear tests of sand (SN) and grey clay (AG) samples, following Mohr-Coulomb failure criterion

Fig. 8. Results for tests on different overburden types.



(a) Oedometric curve obtained from oedometer tests on clay (AG, three samples) and sand (SN)

(b) Oedometric modulus envelope calculated for clay (AG, mean on three samples) and sand (SN)

(c) Hydraulic conductivity determined from oedometer tests of clay (AG, three samples) and sand (SN)

Fig. 9. Results for tests on different overburden types.

As indicated in Table 4, different soil behavior, in terms of slump and cone angle, can be observed when varying moisture content (see column "w").

3.2. Sedimentation tests

Sedimentation tests on clayey and sandy materials were performed. The mechanical stirring was able to separate silty sand lumps, overcoming the cohesion. When the stirring was stopped, coarser sand particles quickly settled according to their diameter, while fines remained in suspension for a longer time, conferring to the water a dark shade (Fig. 6). As far as the clay material was concerned, the strong cohesive and sticky behavior prevented the disruption of clay lumps during stirring, making the mixing action of the blender quite ineffective. Only a small amount of fines remained in suspension, while the majority behaved as a single cohesive lump which immediately settled. This adhesive behavior, which is thought to act also at small scale, resulted in an empirically established sedimentation rate of clay higher than that of sand (Fig. 10). This result can be explained assuming that clay fines in suspension do not settle as separate particles, as ideally described by Stokes' law, but forming micro clods, which corresponds in practical terms to equivalent particles with bigger diameter.

3.3. On-site tests

Detailed studies on different equipment for fragment size production, and on the related properties are rarely available in literature: here it can be cited the case of surface miners [28]. Cone penetration test (CPT) results indicated a poor compaction of the overburden material, with a maximum tip resistance presumably related to undrained shear strength of a saturated cohesive material equal to 2200 kPa (see Table 3) [29].

California bearing ratio (CBR) index indicated a soft and highly deformable soils. Those poor features were confirmed by the plate load test (PLT): only the sand formation allowed to successfully perform the test. Module could not be determined on clayey layers, since the plate sank down without activating the bearing capacity of the soil, as the first load step settlements exceeded the measuring range.

In-situ density measurement results gave values in accordance with those obtained during laboratory density measurements. The difference between wet and dry density indicates a significant void index and, consequently, a high natural moisture content for all investigated soils. It proved to be difficult to reduce the void index as soil hydraulic properties did not allow compaction in short time, evidencing the attitude of water to be retained by the fine fractions.

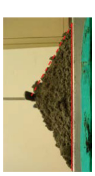
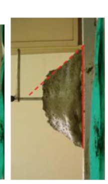
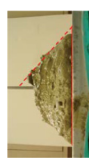
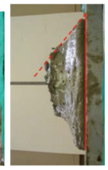
The dump truck crossing test allowed to understand overburden material behavior during a real interaction with heavy site equipment in their operational sequences (Fig. 7). The truck left deep tire marks (up to 80 cm) and in the clay section of the test embankment the rear axle almost touched the ground, revealing poor material compaction and bearing capacity, in accordance with results from other on-site tests discussed above. The strain due to the truck passage occurred together with lateral creep, whose extension did generally not influence the structure and the shape of the embankment (only local damages in some sections required maintenance operations). As a consequence, the effect of soil compaction under the tracks was not consistent. It can be assumed that the fine particles interfere negatively with the draining process, therefore a sort of "bulk displacement" of soil occurred rather than a real reduction of the void ratio.

4. Discussion

4.1. Interpretation of the obtained results

Laboratory tests results showed a certain degree of difference between the examined materials. For clay samples, high vertical strain was observed (up to 20%), indicating a high compressibility

Table 4
Slump tests on three soil types (sand, clay and mix).

Material	Test	Slump (cm)	w (%)	Cone angle (°)	Visual appearance	Material	Test	Slump (cm)	w (%)	Cone angle (°)	Visual appearance	Material	Test	Slump (cm)	w (%)	Cone angle (°)	Visual appearance
	SN1	16	18.8	30			Dry clay rest angle depends upon lumps fragmentation, therefore a laboratory slump test could be misleading										
Sand (SN)	SN2	0	29.8	80		Clay (AG)	AG1	1	54.3	80		Mix (SN + AG)	M1	4.5	47.0	75	
	SN3	12	43.1	56			AG2	7	60.1	64			M2	16	57.3	54	
	SN4	22	45.7	48			AG3	18	73.2	43			M3	20.5	62.9	37	

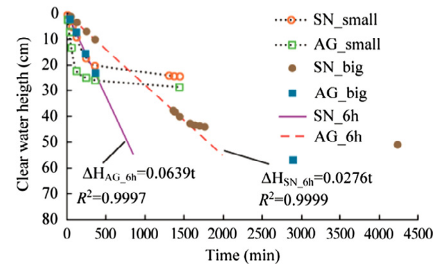


Fig. 10. Sedimentation test results for sand (SN) and clay (AG) in small and big measuring cylinders.

of the material. Accordingly, high settlements are expected over the time. Oedometric moduli are moderately low, especially for clay samples, indicating a low stiffness and poor bearing capacity of the material, which was confirmed by the plate load tests results. The low values of hydraulic conductivity for both clay and sand samples indicated high fine particle content and consequently high plasticity material, which was also found from geotechnical classifications.

Slump tests allowed the qualitatively evaluation of the consistency of the materials: in both cases, the higher the moisture content, the stickier the behavior of the materials was. Clay behavior is particularly critical, especially because of its wide plastic range. This aspect seems to indicate that the material handling could be problematic in wet conditions. Cone angle and cone fall of the tested soils seemed to follow linearly the moisture content when this latter exceeded the plastic limits (see Fig. 11).

Despite the efficiency of the mechanical blender for the sandy material, sedimentation tests showed that neither for clayey sand nor for clay was possible to produce a slurry dense enough to justify the use of the reverse dredging system. As stirring action stopped, particles quickly settled, leaving after couple of minutes a solid concentration in water of few grams per litre, which does not match with the required production rate. As far as the clayey sand overburden was concerned, experiments showed that sedimentation rate was mainly affected by the power of the mechanical blender and by the particle size distribution. Cohesive and sticky behavior is the main issue: mechanical mixing is inefficient, resulting in the formation of big lumps that can lead to a high clogging risk for the dredge apparatus.

4.2. Disposal strategies and limits after analysis results

Alternative options with higher productivities can be identified by considering test results and logistic aspects, with the aim of reducing the number of stages required for transferring the materials, as this represents a saving in terms of machines and energy supply.

Compaction issues particularly depend upon material type. For the investigated clayey soil (classified as CH in ASTM classification), good compaction could only be achieved over a long time (longer than consolidation time), letting water overpressure to dissipate. This means that satisfactory compaction could be reached in Oedometric conditions, with the material confined and subjected to a static and continuous vertical stress over the time. This configuration could be partially reproduced on site by the dumping of subsequent soil layers, provided that high plasticity and clogging behavior would allow this strategy. For sandy soil (classified SC) it could be easier to obtain a good compaction in shorter time, though the high fine particles content could prevent suitable dynamic compaction actions. Being the investigated material excavated and dumped as a mix, clay imposes the predominant material behavior, which was confirmed by the poor performances obtained during on site embankment tests.

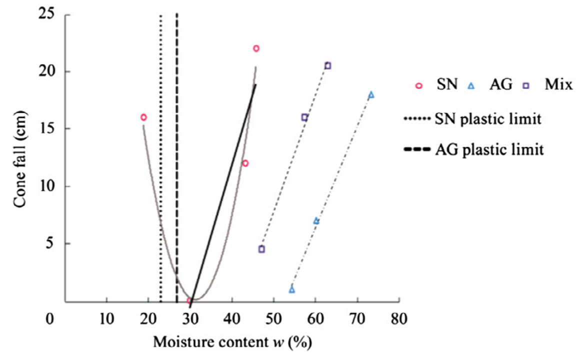
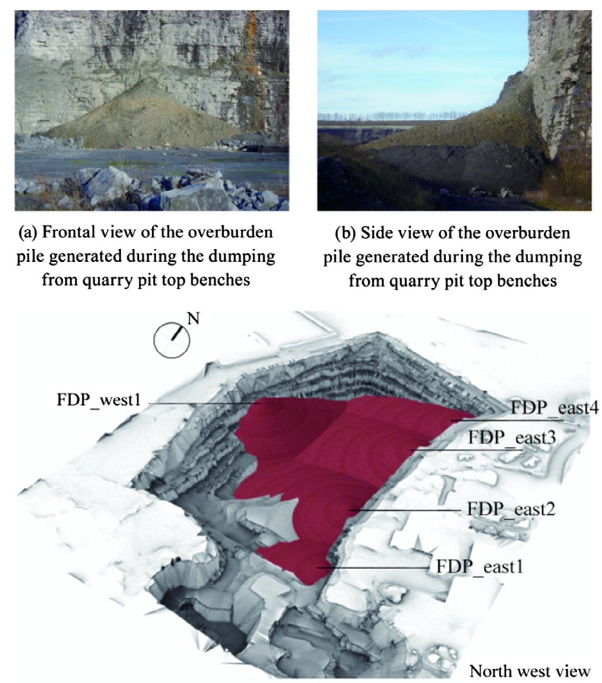


Fig. 11. Cone angle and cone fall of sand of the three tested soil types (sand, clay and mix) compared with the related plastic limits.

The difficulties observed during the transit of the truck on the testing embankment are mainly due to the additional frictional resistance given by the soil and the hazard related to the lack of free space between the ground and the chassis and axles of the trucks. This appeared after few dump truck passages, determining the frequent need for a regularisation of the transit surface by means of dozers or the adoption of techniques for soil improvement, such lime or cement stabilisation, or the inclusion of coarse soils along the main pathways. As a consequence, the expected average speed of the trucks would decrease and the fuel consumption would increase, determining a low global efficiency of the system (i.e., productivity). Moreover, rainfall worsens material physical characteristics, hence in case of rainy weather conditions the solution of hauling and dumping with trucks could not be feasible.

The adoption of a dredging system is common in quarry basin for coarse aggregate exploitation. Its use for reloading and final disposal in the quarry lake could be seen as a natural adaptation of the dredge, but some weaknesses can be outlined. From the geotechnical point of view, a very long consolidation time is necessary due to the highly dispersed soil structure in water. This affects the final material volume and, consequently, the actual possibility of stocking all the overburden material cannot be assured. The environmental issues linked to this solution are related to the dispersion of fine particles due to the dynamics of the suction and pumping of the material. Water treatment system for tackling pollution from leaching phenomena can be expensive. Moreover, turbidity treatment on surface would be required in case the pond water would be needed for industrial purposes. The resulting material structure would not allow any reclamation nor future use of the area, being much dispersed and inherently unstable. There are also some technological concerns, such as pipeline clogging risks, difficulties in operating with a dredge of big dimensions into the pit lake, need for anchoring on the pit walls for floats and pipes, hazard in having personnel on the lake, lack of control of the activities when started (no way back), energetic costs of dredge, limited flexibility in case of need for process adjustment.

The option of discharging the removed material from the contour crest of the quarry directly into the pit by using conveyor belts proved to be feasible according to the performed tests. In such case a main line of belt is feeding lateral discharging points with multiple cantilever extensions, able to distribute the spoil and creating cones at the base of the pit walls. The possible filling volume is influenced by the friction parameters of the spoil and by the water content. The site test (Fig. 12a and b) has been carried out with the progressive discharge of materials from a top bench and subsequently scanning the shape of the dumped pile by means of topographic surveys. On a larger scale some observation have also been carried on existing piles which exhibit both short and long term rest angle. This parameter influences the ratio of filling into the available space, without considering long term settlement and



(a) Frontal view of the overburden pile generated during the dumping from quarry pit top benches

(b) Side view of the overburden pile generated during the dumping from quarry pit top benches

(c) 3D simulation of exhausted quarry pit filling. Overburden is transported on the edge of pit walls by means of a conveyor belt system

Fig. 12. Dumped material pile.

creep development. Numerical modelling has then been carried out (Fig. 12c), thus providing a quantitative and visible assessment on the admissible volume. As a consequence, a sort of "efficiency" of filling of this option can be obtained comparing the potential stocking volume with the required volume to be handled. The option of backfilling from the top crest of the open pit by means of conveyor belts operating from several discharge points has some advantages. It can be proposed when the residual slopes along the open pit walls are steep enough to allow the material to slide and settle, as it is in the case examined.

Fig. 12a and b use a 3D laser scanning to assess the overburden material rest angle. And Fig. 12c shows then the material is dumped directly into the pit from 5 fixed discharge points (FDP), 4 on east side and 1 on west side.

A possible technical improvement is represented by the distribution of the spoil material by using a conveyor belt system, connected with lateral discharging points located at suitable intervals. The strengths of this method are represented by the absence of need for soil stabilization and compaction, by the possible reduction of soil/water contacts and pollutants leaching in case of dry working conditions (i.e., the water table is maintained at a lower level during the working phases of dumping), and by the absence of workers in the pit. The weaknesses are represented by the relatively low filling efficiency, which has to be determined according to the actual consistency of the soils. Moreover, the effects of kinetic energy of the materials dumped from the top need to be understood in terms of real mass kinematics (the consequences in terms of underwater diffusion, mud-flow, debris-flow, rock fall, creep, rest angle stockpile, interaction with different stockpiles development) according to the pit water conditions (i.e., depending on the presence or absence of water in the basin). Noise, dust, vibration have low potential impacts during the soil mass fall. Dispersion of fine particles and need for water treatment are to be considered in case of wet working conditions (i.e., with water filling the pit during the spoil disposal). Difficulties can arise for future reuse of surface area as well as for controlling the water level raise. There would be no possibility of accessing the stockpiles with heavy equipment due to stability and safety issues. A limited flexibility in case of need for process adjustment should also be taken into account.

In the case examined there were limited working spaces along the crest, but this is a local problem and it does not represent a general criterion.

5. Conclusions

Overburden removal and disposal operations in quarry pits are affected by geological, geotechnical, environmental and logistic issues. Methods for handling the materials have to be selected on the basis of the amount of the volume, on the distance from excavation to discharge points and on the consistency of the materials. The possible reuse or reclamation of the site is also to be taken into account, thus the bearing capacity and the stiffness of the deposit is of primary importance.

In this paper the main issues related to the overburden management for large open pit mining operations have been discussed, describing the need of a multidisciplinary approach and of a focused laboratory and on-site test programme. A relevant case has been studied in details, in order to give an example of the required approach adopted for a planned large limestone quarry exploitation. For the selected site, the overburden thickness, the presence of a lake in the open pit and the environmental constraints required detailed investigation and testing to correctly define the behavior of the materials, with the aim of determining the safest and soundest disposal method.

The research allowed to define some key issues for the selection of the proper disposal method:

(1) The reduction of stages for transportation and handling of the materials determines the increase of efficiency.
(2) The characterization of the materials is essential for equipment selection, and it is to be carried out in terms of grain size distribution, consistency and compaction, as these factors have a high influence on the stability and stiffness of the final dumps and on the site reclamation.
(3) The chemical/environmental compatibility is also relevant in case of interference with ground water.
(4) The organization of site operations is fundamental to reduce costs and personnel work; technological choices and installation are strategic in making the difference among the possible methods.

The above listed features arise from the results of material testing and behavior modelling which have been carried out in the described case:

(1) Regional and local investigation on the groundwater conditions;
(2) Geotechnical characterisation directly connected with the alternative options for the overburden handling;
(3) Scaled tests and numerical modelling of the sedimentation dynamics and transportation of suspended particles;
(4) Real scale testing for assessing the compaction of dumped material not yet submerged by the water of the pit lake.

The real case study demonstrated that the proposed approach can be applied for a comprehensive study for a rational and compatible disposal of overburden originated from quarry site preparation, similarly to the case of muck coming from tunnelling excavations. A general methodology can be derived, providing the criteria adopted for the selection of material handling methods in case of relevant overburden volume to be transferred. Several fundamental steps were identified:

(1) To carefully evaluate the site particular aspects, intended as geographic location and surface morphology;
(2) To assess in detail both micro and macro properties of overburden materials from the geotechnical point of view;
(3) To evaluate and compare the efficiency that can be obtained from alternative options of excavation–transportation and dumping waste rock and soil;
(4) To ensure that the final structure stability is achieved and the site is suitable for a possible reclamation procedure;
(5) To evaluate with care the environmental consequences of the dumping–filling phase in relation with surface and ground water quality.

Adaptation is required for other geological (e.g. iron ore pits, gold mine pits, etc.) and morphological scenarios (e.g. flat lands, mountain sides, top mountain removal and valley fillings, variable thickness of overburden, etc.), especially when the control of both surface water and ground water is essential for short and long term operation and for stability issues as well.

Acknowledgments

Thanks are due to Mr G. Torchio for the graphics of the 3D simulation of overburden disposal from fixed discharge points. Special and extended thanks are due to the technical and support staff of CCB in Gaurain (Belgium) and Italcementi CGT in Bergamo (Italy), which supported part of this research by means of a research contract with Politecnico of Turin, DIATI (coordinator A. Godio).

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