

MANAGING VALORIZATION OF DREDGED SEDIMENTS VIA AN INNOVATIVE MATHEMATICAL MODEL USED FOR CIVIL ENGINEERING APPLICATION

M.Benzerzour, N.Abriak, R.Mansi,

Civil & Environmental Engineering department, Ecole Mines Douai, 59500 Douai, France

ABSTRACT: Several years ago, global consumption of materials used in the field of Civil Engineering and especially materials for public works, has strongly growth. The use of marine and/or river dredged sediments presents a promising alternative to deal with the problematic of sustainable development. In this paper, we study a management problem of existing treatments for these sediments. Looking to the economical and legislative obligations associated with the treatment process, these operations present one of the main encountered problems during the valorization process of sediments. The solution for this problem is to find an optimal set of treatments respecting these economical and legislative constraints. This optimal solution is obtained by solving a non-linear mathematical model with binaries variables. The proposed resolution algorithm for this model is based on a linearization of the nonlinear constraints in order to solve a simple problem using a solver.

Keywords: dredged sediments, valorization, mathematical model, civil engineering

1. INTRODUCTION

The exploration and the exploitation of existing and future fields are increasingly regulated looking to the economic, social and environmental reasons. The important need to conserve environment and to manage the valorisation of wastes, presents an unavoidable industrial stakes looking to its financial and environment impact.

Each year, huge quantity (600 million m³/year [4]) of sediments and sands resulting from the dredged operations executed to maintaining and to ensure the accessibility of ports and waterways. Port authorities have to find solutions for integrated and enduring managements of these sediments [15]. Several ways of valorization in Civil Engineering applications are possible, such as the foundation of roads, dikes and landscaped mounds, concrete and artificial aggregates [6,8]. However, this management remains complex and mainly depends on several principals parameters environmental, mechanical and economic parameters.

2. SCIENTIFIC APPROACH

Several experiments of valorization are realized in the context of European research projects such as: experimental roads based on marine sediments (ex: experimental road of 200 m

in Caen, France (project SETARMS); implementation of dikes with river sediments (Project PRISMA).

These scientific researches currently instrumented give very good results, but the sustainability of the valorization processes is not acquired and meets strong mechanical, economic and environmental challenges. Indeed, these valorizations in road construction require many specific treatments such as dehydration, de-pollution mineralogical and organic treatments, and reinforcement treatment by adding hydraulic binders and/or granules. Moreover, these valorizations process should deal with the optimizations problems of deposits sediments available locally and costs of treatment.

In the diagram below, we present the global scientific approach for the development of dredged sediments in road applications.

The valorisation of dredged sediment is composed on six main steps:

- i. Zoning: localization of the potential deposit to be dredged
- ii. Dredging: which can be mechanical or hydraulic
- iii. Storage: according to the environmental nature of the sediment
- iv. Treatment / formulation
- v. Laboratory validation
- vi. In-situ validation

One of the most important and delicate steps in the valorisation process is the treatment and the formulation of new materials based on sediments. It requires a process of optimization and reflection, often difficult. It also requires different treatments to improve sediment characteristics respecting mechanical, environmental and economic constraints of feasibility. Several treatment techniques exist such as reducing the pollution using electrokinetic methods [2]; reducing the organic matter by bioremediation technical or by calcinations [11]; reducing the water content by filter press or natural settling [7].

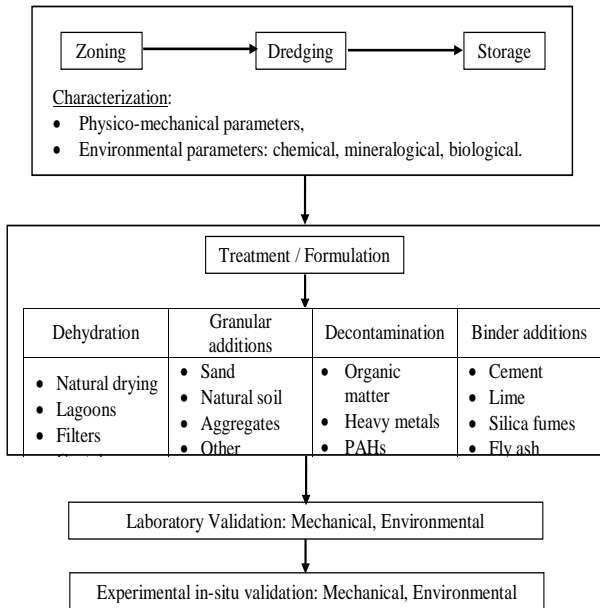


Figure 1: Valorization process

Formulation's methods look to increase the resistance of the material. These formulations are mainly done by granular additions [6] and also by additions of hydraulic binder [12, 13]. The optimization of these treatment methods and formulation is mainly based on the economic, mechanical and environmental criteria.

3. MATHEMATICAL MODEL

The objective of our research is to find a solution that provides an acceptable material for valuation in road construction. This solution is in the form of a mixture of sediment with one or more noble materials (ex: sand) which is

subjected to a set of physical and chemical treatments in order to respond to requirements and normative constraints. We are interested only by the chemical part in order to solve a choice treatments problem.

Before presenting the different constraints of our model, we introduce a set of variables X associated with each sediment. $x_i \in X$ is a binary variable which equal to 1 if the sediment i is used and equal to 0 else, for $i = 1, \dots, n$ where n is the number of sediments. The first constraint should ensure the choice of one and only one sediment. The mixture of several sediments can activate a chemical interaction between elements witch disturbs strongly the efficiency of any programmed treatment. This constraint can be presented by:

$$\sum_{i=1}^n x_i = 1 \quad (1)$$

The set of treatments applied on sediment depends principally on its pollution and on the field of valorisation. In this paper we consider the case of road application.

3.1. Chemical constraints

The environmental aspect in the construction of roads based on a sub product or waste is one of the most important constraints according to the regulation (Guide SETRA). Each country requires some limit values for polluting elements in the raw materials used for construction. The acceptability limits to use materials in road application are mainly concerning the concentration of contaminants elements in these materials. For example, the limits required in France are given in the next table.

These limits can change from a country to another, but the constraints are always present. To make an acceptable material (sediment in our case) for road construction, it must be cleaned. In other world, it must be exposed to a set of known techniques of pre-treatment and treatment to reduce the concentration of contaminants elements if necessary. We know that each treatment has an impact on all contaminant elements. For example, the electrokinetic treatment can reduce the concentration percentage of some heavy metals such as Zn up to 32% [2] and the treatment with remediation can reduce it further to 10% [3].

Table 1: Legislative limits for chemical elements in France

Elements	Limit (mg/kl)
TOC: total organic carbon	60000
BTEX : Benzene, toluene, ethylbenzene and xylenes	6
PCB : Polyvinyl biphenyls	1
HCT : total hydrocarbons	500
PAH : Polycyclic aromatic hydrocarbons	50
As	2
Ba	100
Cd	1
Cr : total	10
Cu	50
Hg	0.2
Mo	10
Ni	10
Pb	10
Sb	0.7
Se	0.5
Zn	50
Fluoride	150
chloride	15000
Sulfate	20000
fraction soluble	60000

Therefore, the application of the two previous treatments can reduce the concentration of Zn until $(32\% \times 10\% = 3.2\%)$ of its initial concentration. We note that in practice rarely are the cases where the sediment requires multiple treatments.

To model this constraint, we introduce the binary variables T_t for $t = 1, \dots, |T|$ where $|T|$ is the number of treatments:

$$T_t = \begin{cases} 1 & \text{for treatment } t \\ 0 & \text{else} \end{cases}$$

$q_i^j \in [0,1]$ is a continuous value that indicates the quantity of the contaminant element j in the used sediment i and Q^j presents the limit associated with the element j . Denote by $|Q|$ the number of elements. The parameter δ_{ti}^j represents the reduction percentage associated with the element j and resulting by the application of treatment t on the sediment i . Environmental constraints can then be written as follows:

$$q_i^j \prod_{t=1}^{|T|} (1 - \delta_{ti}^j T_t) \leq Q^j + (1 - x_i)M \quad (2)$$

$$i = 1, \dots, n, \quad j = 1, \dots, |Q|$$

With M is a large positive constant which helps to relax the constraint when the sediment i is not used ($x_i = 0$). The product $\prod_{t=1}^{|T|} (1 - \delta_{ti}^j T_t)$ models the reduction of the percentage of the concentration q_i^j .

Other constraints should be respected concerning the incompatibility of using two or more treatments together.

$$\sum_{t \in C_T^k} T_t \leq 1 \quad (3)$$

$$k = 1, \dots, |C_T|$$

3.2. Objective function

The objective of our mathematical model is to find an acceptable solution for road application with a minimum costs. These costs are divided into two parts. The first one is concerning the acquisition and/or the dredging operations, presented by the vector $C^1 = (c_1^1, \dots, c_n^1)$ and the second one is the cost of treatments presented by the vector $C^2 = (c_1^2, \dots, c_{|T|}^2)$. The objective function is presented then by:

$$\text{Min} \quad \sum_{i=1}^n c_i^1 x_i + \sum_{t=1}^{|T|} c_t^2 T_t \quad (4)$$

3.3. General Presentation of mathematical model

The mathematical model for the problem of valorization of sediments is presented by the following Quadratic MIP 0-1 problem. This model is non-linear because of constraints (2).

$$\begin{aligned} \text{Min} \quad & \sum_{i=1}^n c_i^1 x_i + \sum_{t=1}^{|T|} c_t^2 T_t \quad (4) \\ \text{s. t.} \quad & \sum_{i=1}^n x_i = 1 \quad (1) \end{aligned}$$

$$q_i^j \prod_{t=1}^{|T|} (1 - \delta_{ti}^j T_t) \leq Q^j + (1 - x_i)M \quad (2)$$

$$i = 1, \dots, n, \quad j = 1, \dots, |Q|$$

$$\sum_{t \in C_h^k} T_t \leq 1 \tag{3}$$

$$k = 1, \dots, |C_T|$$

4. HEURISTIC

4.1. Linearization of nonlinear constraints

Constraints (2) are nonlinear. They pose a particular difficult to solve our problem. In order to simplify our model, it is necessary to linearize these constraints, i.e. the quadratic expression $\Phi_i^{|T|} = \prod_{t=1}^{|T|} (1 - \delta_{ti} T_t)$. So we list all the combinations of variables T_t . This expensive process ($2^{|T|}$ cases) is justified by the limited number of possible treatments (at most $|T| = 20$). The linearization of $\Phi_i^{|T|}$ requires the introduction of new variable y_h associated with the combination of variables C_h^T (h is the index of the combination):

$$y_h = \begin{cases} 1 & \text{if } \forall t \in C_h^T, T_t = 1; \forall t \notin C_h^T, T_t = 0 \\ 0 & \text{else} \end{cases}$$

The associated cost with y_h is calculated then by $c_h^2 = (\sum_{t \in C_h^T} c_t^2)$ and the coefficients of y_h are $a_{ih}^j = \prod_{t \in C_h^T} (1 - \delta_{ti}^j)$. For example: the combination $C_h^T = \{2,3,4\}$ of variables is presented by the new binary variable y_h with cost $c_h^2 = (c_2^2 + c_3^2 + c_4^2)$ and coefficients $a_{ih}^j = (1 - \delta_{2i}^j) \times (1 - \delta_{3i}^j) \times (1 - \delta_{4i}^j)$.

To finalize this linearization, we add the constraint (5) to impose the choice of a single treatment combination as possible.

$$\sum_{h=1}^{2^{|T|}} y_h \leq 1 \tag{5}$$

In similar cases in the literature, an alternative approach based on the column generation algorithm [1] is adopted i.e. only promising variables (combinations) will be generated. This is difficult in our case because of the non-linearity of $\Phi_i^{|T|}$. So to solve our problem, we will use the opposite approach of the column generation

algorithm. More specifically, we will generate all the variables (combinations). Note that the variables y will not be generated at the same time, but they will be added to the model step by step during the resolution. In practice, the number of treatments for sediment is very limited, which leads us to give priority to the small combinations of treatment. Then, we will consider in the beginning a combination of two treatments and after we generate a combinations of three, four and five treatments if not more. This proposal linearization for the constraint (2) allows us to eliminate the constraint (3). This constraint will be respected during the generation of different combinations. The new linear model is presented below.

$$\text{Min } \sum_{i=1}^n c_i^1 x_i + \sum_{t=1}^{|T|} c_t^2 T_t \tag{4}$$

$$\text{s. t. } \sum_{i=1}^n x_i = 1 \tag{1}$$

$$q_i^j \sum_{h=1}^{2^{|T|}} a_{ih}^j y_h \leq Q^j + (1 - x_i)M \tag{2}$$

$$i = 1, \dots, n, \quad j = 1, \dots, |Q|$$

$$\sum_{h=1}^{2^{|T|}} y_h \leq 1 \tag{5}$$

$$x \in \{0,1\}^n, \quad y_h \in \{0,1\},$$

$$h = 1, \dots, 2^{|T|}$$

The resolution of this mathematical model can be done using an approximate method (heuristic for MIP 0-1 problems) or using an exact algorithms. The latters can spend a large execution time. To solve our model, we used a free solver Lpsolve. Other more efficient commercial solvers can also be used; for example Cplex. These solvers are principally based on exact algorithms.

5. CONCLUSIONS

In this paper, we proposed a mathematical model that optimizes the management and the choice of used treatments for a decontamination of marine and/or river sediments. This problem has been modelled as a nonlinear mathematical model with mixed variables. Our solving approach is mainly based on a linearization of this model. This linearization is based on the enumeration of all non-linear combinations.

Finally, the simplified mathematical model is solved using a numerical solver. This mathematical model can be widened to other parameters, in particular, physical and mechanical parameters, in order to use sediments as alternative materials.

6. REFERENCES

- [1] George, B, Dantzig and Philip, Wolfe Decomposition Principle for Linear Programs. *Operations Research*, 8(3): 101–111, 1960.
- [2] Kim, K.J., Kim, D.H., Yoo, J.C., Baek, K. Electrokinetic extraction of heavy metals from dredged marine sediment. *Separation and Purification Tech.*, 79: 164–169, 2011.
- [3] Lors, C., Tiffreau, C., Laboudigue, A. Effects of bacterial activities on the release of heavy metals from contaminated dredged sediments. *Chemosphere*, 56:619–630, 2004.
- [4] Jones-Lee, A., Lee, G.F. *Water Quality Aspects of Dredged Sediment Management*, *Water Encyclopedia: Water Quality and Resource Development*. Wiley, Hoboken, NJ: 122-127, 2005.
- [5] Chen, H.J., Yang, M.D., Tang, C.W., Wang, S.Y. Producing synthetic lightweight aggregates from reservoir sediments. *Construction and Building Materials*, 28: 387-394, 2012.
- [6] Zentar, R., Dubois, V., Abriak, N Mechanical behavior and environmental impacts of a test road built with marine dredged sediments. *Resources, Conservation and Recycling*, 52: 947–954, 2008.
- [7] Dubois, V., Abriak, N., Zentar, R., Ballivy, G The use of marine sediments as a pavement base material. *Waste Management*, 29: 774-782, 2009.
- [8] Miraoui, M., Zentar, R., Abriak, N Road material basis in dredged sediment and basic oxygen furnace steel slag. *Construction and Building Materials*, 30: 309-319, 2012.
- [9] Tang, C.W. Chen, H.J., Wang, S.Y., Spaulding, J. Production of synthetic lightweight aggregate using reservoir sediments for concrete and masonry. *Cement and Concrete Composites*, 33: 292-300, 2011.
- [10] Troalen, J.P., Duron, C., Hagnere, C. Traitement de vases de l'estuaire de la Seine. *Revue Française de Géotechnique*, 77: 31-36, 1996.
- [11] Lafhaj, Z., Samara, M., Agostini, F., Boucard, L., Skoczylas, F., Depelseñaire, G Polluted river sediments from the North region of France: Treatment with Novosol process and valorization in clay bricks. *Construction and Building Materials*, 22: 755-762, 2008.
- [12] Tremblay H., Leroueil S., Locat J. Influence of the nature of organic matter on the soil stabilization with cement. *Canadian Geotechnical Journal*, 39: 535-546, 2002.
- [13] Satone, H., Mamiya, T., Harunari, A., Mori, T., Tsubaki, T. Solidification Mechanism of the Sediment Formed by Particle Settling — Analysis of the Final State of the Sediment. *Original Research Article Advanced Powder Technology*, 19(3): 293-306, 2008.
- [14] Levacher, D., Sanchez, M. Characterization of marine sediments for a reuse inland disposal land embankment. *European Journal of Environmental and Civil Engineering*, 15: 167-178, 2011.
- [15] Miyazato, N., Osaki, M., Toda, M., Kimura, K., and co. Partial sediment dredging method developed for conserving ecosystem and recycling sedimentary material. *International journal of GEOMATE: geotechnique, construction materials and environment*, 3(1), 280-284, 2012.

International Journal of GEOMATE, Oct., 2016, Vol. 11, Issue 26, pp. 2679-2683.

MS No. 5199 received on June 09, 2015 and reviewed under GEOMATE publication policies. Copyright © 2016, Int. J. of GEOMATE. All rights reserved, including the making of copies unless permission is obtained from the copyright proprietors. Pertinent discussion including authors' closure, if any, will be published in Oct. 2017 if the discussion is received by April 2017.

Corresponding Author: Mahfoud benzerzour
