PRACTICAL HAUL ROAD DESIGN METHODOLOGY APPLICATION BASED ON SITE CHARACTERIZATION

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ABSTRACT

Most of the surface mines use a truck system for hauling material, which can represent about 40% of their operational costs (OPEX). Poor road design can lead to many problems and additional costs, such as an increase in fuel and tyre consumption, ergonomic problems for operators (back problems), increased work accident risk and productivity losses. Haul roads should enable trucks to drive at their maximum safe speed, and it is estimated that a 1% increase in the rolling resistance would reduce the truck speed by 22% on high speed surface roads and 10% on pit ramps. Most of the mine roads are designed by empirical methods or just constructed by dumping and spreading material. It has been shown that such methods have the potential for increased costs as a result of the poor design. Mechanistic design, on the other hand, allows mine planners to determine the layer thickness based on limiting strain values according to local in-situ materials.

The objective of the paper is to present a low-cost approach, to design a haul road based on limiting strain values for layer thickness determination using the Dynamic Cone Penetrometer (DCP) test assessment. As a case study, a formal haul road design procedure is applied in a typical Brazilian quarry. The design process started with the construction of a special test device, the DCP. It is used for on-site material strength assessment. DCP results are correlated with California Bearing Ratio (CBR) for on-site material characterization, where poor soils should be removed and replaced or just covered with a sufficient layer thickness of selected blasted rock. Wearing course material selection is based on laboratory tests such as Atterberg Limits and particle size distribution. This process provides a vehicle friendly road that reduces operational costs such as truck maintenance costs, fuel and tyre consumption, cycle times and especially for production performance improvement through the allowance of driving safely at higher speeds. It was found that the formal design process had major economic and operational benefits.

KEYWORDS

Haul road design, Dynamic Cone Penetrometer, in-situ characterization, Wearing course selection, Structural design

INTRODUCTION

The increase in mine production led to the utilization of larger off-highway trucks, with capacities of 400t. Although, truck haulage costs can account to up to 40% of the total mining costs, mine haul roads are mostly designed based on empirical methodology which will result in inappropriate design. Good haul roads are a key to successful surface mining operations. Poorly designed, constructed and maintained roads are major contributors to high haulage costs and pose safety hazards (Hustrulid and Kuchta, 2006). A road well designed, built and in good traffic conditions will allow vehicles to ride safely and efficiently. Moreover, a good road will also allow trucks to operate at their maximum safe speed. According to Kaufman and Ault (1977) a stable road base is one of the most important fundamentals of road design. Placement of a road surface over any material that cannot adequately support the weight of traversing traffic will severely hamper vehicular mobility and drivability. Moreover, lack of a sufficiently stable bearing material beneath the road surface will permit excessive rutting, sinking, and faster overall deterioration of the travelled way. Thus, an intense frequency of maintenance will be necessary to keep the road passable.

The aim of this paper is to present a low cost haul road design approach based on site characterization through the utilization of Dynamic Cone Penetrometer (DCP) for subgrade strength assessment and simple laboratory tests for wearing course material characterization and selection. DCP results were correlated with CBR values, for an initial structural design. Subsequently a CBR based design was assessed, compared and optimized with a mechanistic approach based on limiting strain values using the software EVERSTRESS for stress and strain calculation in the layers. Special attention was given to the functional project, as the CBR design approach does take into account the wearing course material selection. For the particle size distribution, the guideline limits established by the National Department of Transport Infrastructure (DNIT) for graded crushed stone, combined with Atterberg limits and CBR testing, were used. This approach presented good potential for initial wearing course composition determination. Final composition was based on the guidelines established by Thompson and Visser (1999) for wearing course material for ideal functional performance.

CASE STUDY

The project was developed at the Falchetti granite aggregate production unit, located in southern Brazil. The quarry is developed as traditional side hill mining moving towards an open pit with daily production capacity of 3000t. Historically, haul roads were designed on the quarry by simply dumping and spreading material over the existing subgrade. Lack of design for the haul roads, resulted in high maintenance costs for the truck fleet, at the same time reducing its availability. Also, the company did not use proper equipment like roller, grader or dozer equipment for road building, usually the company used a wheel loader, which is not adequate for the service, as it takes too long to do the work and the result is not adequate.

Actual access to the benches is taken through a ramp connecting the different levels of the quarry, as may be seen in Figure 1. The main ramp was built long time ago and is located west in the pit (to the right of the pit in Figure 1). The ramp presents several geometrical problems, firstly it was not built with a constant grade, presenting 16% on the initial part, 20% on the central part and 25% at final part. This design leads to excessive trucks maintenance, inefficient production and hauling costs increase. Secondly, the road is a two way path and it is not wide enough to allow two trucks to cross simultaneously, often resulting in the empty truck waiting at the bottom of the ramp, delaying the hauling/loading cycle. On the functional point of view, the most common defects noticed were dustiness, loose material and potholes. In the loading area it is common to have tire cutting due to loose material on the platform, resulting in truck maintenance cost increase and production losses as the company uses only a few haulage trucks.

Figure 1: Quarry overview

The pit will reach its eastern limit at the end of this year and will begin its expansion to the west once environmental permits are obtained. The expansion project requires the main access to be relocated allowing the company to extend the quarry´s life. The main goals of the new road project are: to postpone new haul truck purchases, as the transport distance is increasing, increase productivity and system efficiency and also maintenance costs reduction of the actual transportation fleet.

METHODOLOGY

When designing a new road, the first step is to investigate the material where it will be built over, once identified poor soils it should be removed and replaced by superior material or, when there is no adequate material available, structural design must consider sufficient cover thickness on top of the weak soil. It is generally cheaper, in terms of construction costs, to remove weak material and substitute it, instead of reinforcing the pavement. For the in situ material strength assessment, a DCP was manufactured at the quarry, following the design from the Minnesota Department of Transportation – Mn/DOT (Minnesota, 1993). As shown in Figure 2, the DCP consists of a 16mm diameter steel rod, to which a 20 mm 60° conical end is attached. It penetrates into the soil by dropping an 8kg hammer that slides on a steel rod, at a constant height of 575mm. The DCP can be found in the market for approximately US$ 600, considering the actual dollar exchange rate, the equipment would cost around R$ 2.000,00. The "home made" DCP cost was estimated in R$ 300,00, which is 15% of the commercial price. Its construction is simple, cheap and can easily be done at any mine site.

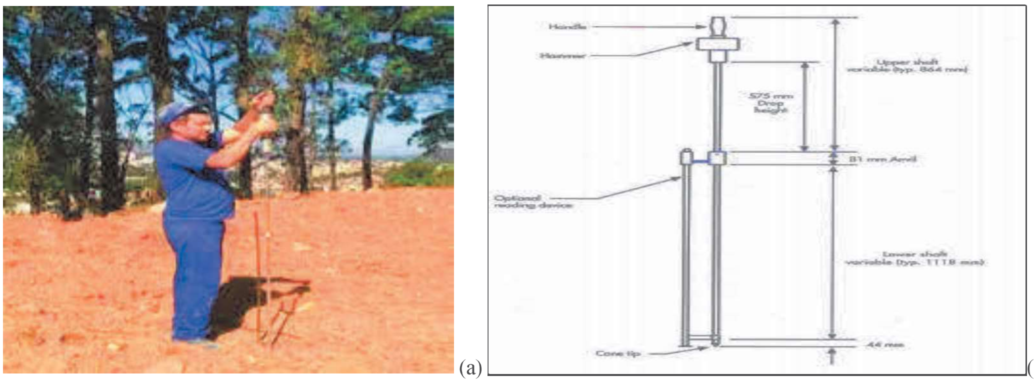

Figure 2: Field testing with DCP (a) / Mn DOT DCP Design (b)

The soil was investigated with DCP for in situ strength assessment and samples were also sent to a soils laboratory for Atterberg limits test and CBR value determination. Several correlations between the DCP results and CBR values have been developed by a number of authors (Livneh & Ishia, 1987; Webster *et al*., 1992; Trichês & Cardoso, 1998). Considering the study of Trichês and Cardoso (1998) developed in the same region in the south of Santa Catarina State over soils formed from similar geology, equation (1) was used. For mechanistic design the subgrade resilient modulus (E) was estimated through De Beer (1991), according equation (2).

$$CBR = 512{,}64 \times PR^{-1{,}25} \tag{1}$$

$$\log E = 3{,}05 - 1{,}07 \log PR \tag{2}$$

Where:

PR = DCP Penetration rate (mm/blow)

Initial structural design was based on the CBR method through its design curves, as shown in Figure 3. This methodology requires that CBR values and wheel loadings are first determined. It is important to mention that, although the method is simple, well understood and can give fairly good design guidelines for most haul roads, it should only be used as a guideline for the critical strain based method.

For the critical strain limit evaluation, the elastic modulus of the base and wearing course materials was determined from past work in the region. It is hard to evaluate mine haul road materials due to its dimensions (too coarse). Although it is fundamental to obtain materials modulus for mechanistic design, most resilient modulus testing equipment available does not support the large haul road particle size distribution. One alternative is to use equipment's such as light weight deflectometer and Benkelman beam for back calculation of layers' modulus. Another alternative is to estimate the modulus through references, such as the suggested values for granular materials presented by Thompson and Visser (1999).

Several studies have been developed in the region during the duplication works of the BR-101 federal highway. Oliveira (2000), in his work evaluates the mechanical behavior of crushed stone through back calculation, obtaining an elastic modulus of 208,5 MPa. Fernandes (2000), evaluated the mechanical behavior of graded crushed stone obtaining a modulus of 166 MPa by back calculation. The materials evaluated in both studies of Oliveira (2000) and Fernandes (2000) were obtained from a granite rock with similar characteristics of the Falchetti´s granite quarry. Although, these values are lower than suggested by Thompson and Visser (1999) they were used in this study considering they are representative of the available materials.

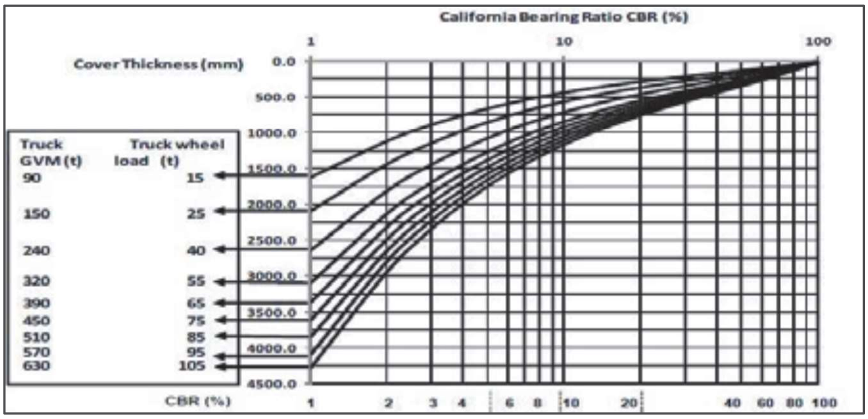

Figure 3: CBR design curves

Special attention was given to the wearing course material selection, as it does not take into account the properties of the surface material. Its composition was based on the grain size limits established on the DNIT standard for graded gravel. Thompson and Visser (1999) recommended parameter specifications for optimum functional performance, the authors suggested that based on shrinkage product and grading coefficient it is possible to predict wearing course defects. Figure 4 shows the graph to select wearing course material for ideal performance. Shrinkage product (Sp) and grading coefficient (Gc) can be calculated by equations (3) and (4), respectively.

$$Sp = LS \times P425 \tag{3}$$

$$Gc = \frac{(P265-P2)x\,P475}{100} \tag{4}$$

Where:

LS = Bar linear shrinkage (can be approximated with the Plasticity index divided by two)

P425 = Percent passing 0,425mm sieve

P2 = Percent passing 2mm sieve

P265 = Percent passing 26,5mm sieve

P475 = Percent passing 4,75mm sieve

In figure 4, two areas are recommended for adequate materials ranges, where areas 1 and 2 are considered Ideal (1) and Operable (2), respectively. The designed wearing course material presented a Gc = 31,04 and Sp = 166,85 and it is represented in the graph by the yellow dot, falling in the operable area. However, it is expected that this material will present some wet skid resistance and loose material if not correctly maintained.

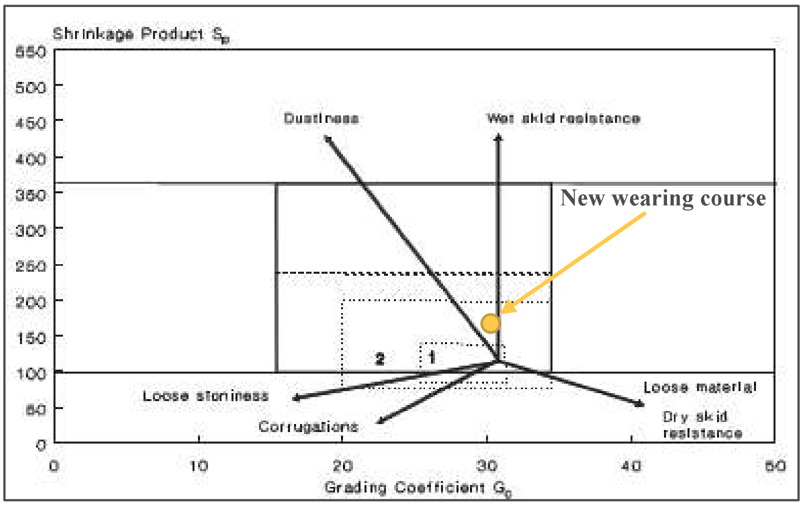

Figure 4: Material selection ranges, source: (Thompson & Visser, 1999).

RESULTS

There were made 10 DCP tests along the axis of the new road to characterize the in situ material. Soil strength was determined defining that weak material (CBR lower than 10%) that should be removed to a depth of 700mm, as shown in Figure 5(b). In the other hand, terrain profile requires cutting and filling for haul road building, where cutting volumes are considerably higher than filling. As the quarry has little space for waste storage, deeper cutting would result in an excess of waste material to be disposed. Also, a 10% CBR value is considered satisfactory for the subgrade layer requiring an acceptable cover thickness. Considering those aspects, the decision was to use material with CBR value of 10% or higher as base material, compacting the material during construction.

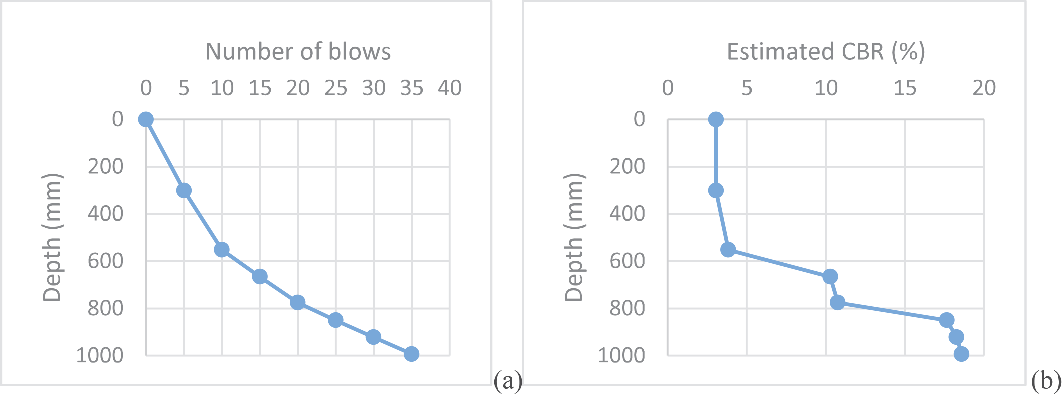

Figura 5: DCP results.

Surface layer design is slightly different from the other layers considering it must meet the general requirements as for the other layers, the design should also take care of operational aspects such as dust control, smoothness of surface, traction and rolling resistance. Material selection is usually based on local experience or guidelines related to unpaved public road construction. However, the unique service condition experienced by mine haul roads requires development of specifications tailored to those particular needs (Thompson and Visser, 2000). Wearing course material selection was based on the DNIT standards for graded crushed stone and the S_p x G_c graphic limits established by Thompson and Visser (1999). The resulting material was produced by mixing three materials in the crushing plant to ensure the correct grain size distribution and the final homogenization was made using the grader during construction.

Compacted natural gravel and crushed rock and gravel mixtures are widely used in surface mines for road construction, especially for the base and wearing layers. These materials can yield low rolling resistance and high traction, and can be constructed and maintained at a relatively low cost (Tannant and Regensburg, 2001). The mixture is composed of ¾" aggregate, 3/8" aggregate and undersized material from the secondary crusher as shown in Figure 6. Undersized material is a low cost material as it is currently discarded by the company, when studying wearing course material selection, mine planners should always look for waste material as a way of lowering the cost. Furthermore, it should also take into consideration the benefit of using waste material in the construction, reducing environmental impact with disposal.

GRADED CRUSHED STONE COMPOSITION							
ASTM	mm	DNIT - Env A		Mixture	Working Env		Tolerance
1"	25,4	100	100	100	100	100	+/- 7
3/8"	9,5	30	65	61	54	68	+/- 7
n°4	4,8	25	55	39	34	44	+/- 5
n°10	2	15	40	23	18	28	+/- 5
n°40	0,42	8	20	12	10	14	+/- 2
n°200	0,075	2	8	5	3	7	+/- 2

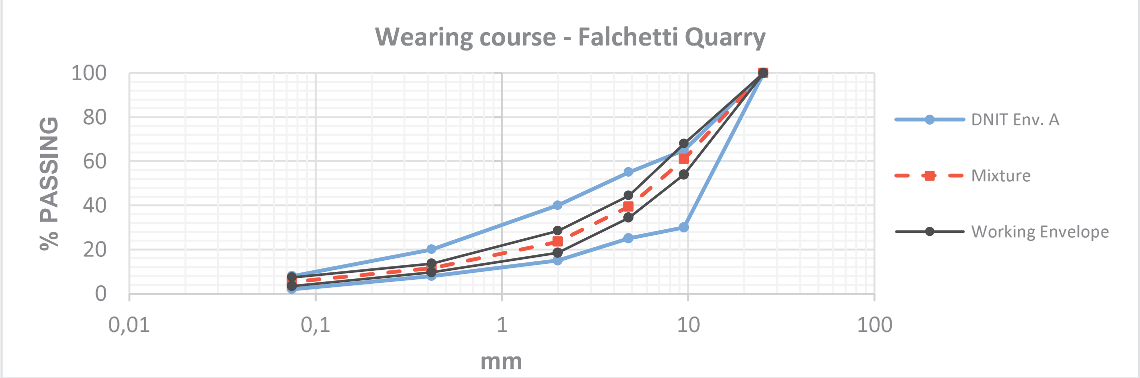

Figure 6: Wearing course composition.

The structural capacity was determined for the largest truck, a Volvo FMX 460 with 22m³ capacity. The truck has an empty operating mass of 18.930 kg and gross operating mass of 60.860 kg, resulting in a maximum wheel load of 4.944,88 kg on the rear wheels. This information, with the CBR value of the soil, wearing course and base material, was used to determine the total required cover thickness through the CBR design method. Wearing course material CBR value was determined from laboratory testing as 103%. Crushed stone base material CBR value was estimated from literature, and the value of 300% was adopted. The total cover thickness obtained was of 280 mm, comprised of 170 mm of base material and 110 mm of wearing course material.

According Tannant and Regensburg (2001), failure in the CBR method is assumed to occur when the tire penetrates a haul road layer or an upper layer´s material penetrates into the lower one, thus causing failure of the structure. Failure can occur even before such condition happens. The haul road cross-section acts as a layered beam structure. Under excessive strain, this structure can no longer act as a beam, thus losing strength, and failure becomes imminent. Consequently, it can be expected that a design using the CBR method would result in under-design in most cases, but sometimes in cases where haul roads are designed for a very short life, the CBR method can be over-conservative.

Haul road design by the CBR method was evaluated using EVERSTRESS to check if maximum vertical strain values exceeds the limiting design value of 2000 με. It was found that the design provided by CBR method, is undersized as shown in Figure 7 (blue line) and will not give enough support. Optimization of the CBR method, with the limiting strain value of 2000 microstrain, was carried out to obtain better structural response to the applied loads. As can be seen in Figure 7, using the critical strain limit design does not exceed the limiting design value for vertical strain (orange line). The optimized structural design suggests a 200mm of wearing and a 250mm thickness of base on top of a subgrade with a minimum 10% CBR. The haul road thickness had to be increased by 60% in order to fulfill the proposed design criteria, especially the limiting strain value. Although, haul road construction cost is higher according the mechanistic desing, as more quality material is used, requiring more compaction and grading activities, the long term benefits are incomparable with this additional cost. It is expected that trucks will be allowed to drive faster, from 20km/h to 30km/h, an increase of 50%. The production cost per ton will be reduced significantly as it will be possible to crush more material with the same structure considering the company has installed capacity with the excavator and loading equipment and also in the crusher, we must say that the trucks are the bottle neck so far.

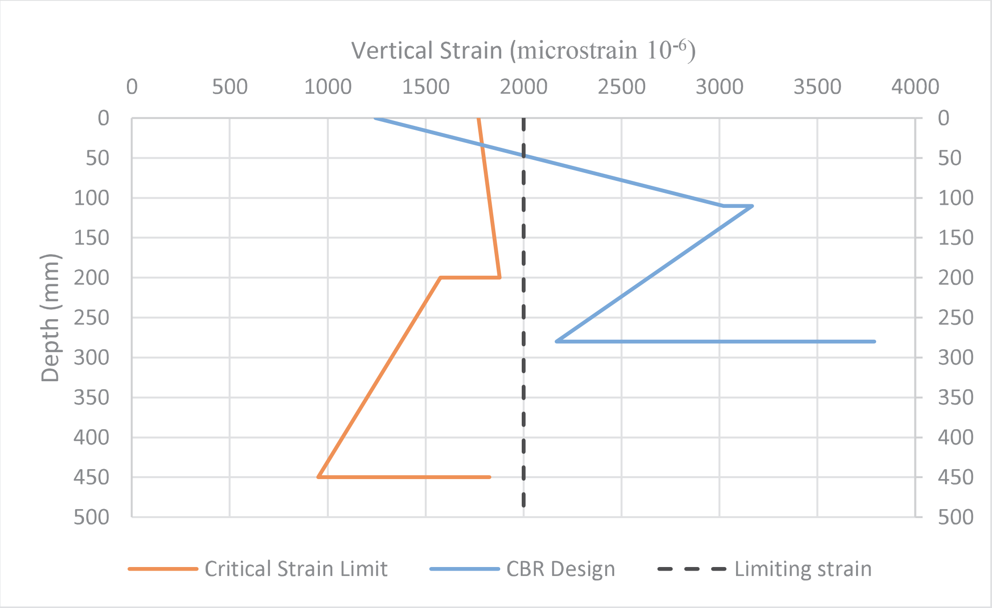

Figure 7: Design method comparison

Figure 8 shows the new wearing course and old haul road showing what was considered as sub grade material for the new road.

Figure 8: New haul road (a) and previous access (b)

CONCLUSIONS

Historical haul road design methods present deficiencies that result in operational underperformance. Lack of information about the in-situ soil over which the road is to be built is a major problem. Mining activity is highly dynamic and sometimes mine planners do not have enough time to evaluate materials, as it would take a few days for a laboratory to characterize. The DCP has been widely used during road construction or maintenance around the world due to its simplicity, low-cost, flexibility and prompt results. Moreover, it has been shown that CBR values can be obtained with high level of confidence from the DCP relationship. It is fundamental that mine planners know the resistance of the on-site material they are going to build a haul road, as sufficient cover thickness must be provided to protect the weak in-situ material from the wheel loads and volume of traffic imposed by trucks.

The CBR method should only be used for haul road design as an initial guideline for the mechanistic method. The CBR method considers failure to occur when a tire penetrates a haul road layer, but failure may occur even before it happens. The mechanistic method, on the other hand, considers failure to occur when the strain at any point exceeds the critical strain limit. The value determined as critical strain limit may vary, depending on the design life of the road and traffic intensity, but usual values are in the range of 1500-2000 microstrain. The material selected and used to build this new road presented a capacity of support that respects this limit and was optimized by the mechanistic method, after using a CBR approach as a start, providing a design with 200 mm for wearing course and 250 for base.

The CBR method does not consider wearing course material design making material selection for the surface layer arbitrary. It has been observed that DNIT standard for graded crushed stone combined with Thompson and Visser (1999) parameter specification may be used for wearing course material selection, indicating a good performance layer with low dust index.

This case study has shown a practical and simplified method of haul road design which provides an adequate structural thickness and a vehicle friendly wearing course. The method can be replicated in any mine. Although the new road is not yet in use by the time of writing the paper, initial cost benefits will be presented at the conference during the presentation.

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