Study on the slaking characteristics of soft rock engineered slopes at a hydroelectric station in Southwest of China

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Abstract: Soft rock is widely distributed in the presented engineered which can be divided into four kinds such as argillised seams, coal, carbonaceous shale, and pelitic siltstone. The spatial distribution of the soft rock and the slaking characteristics directly affect the stability of the slope as well as the design of anchoring and other supports. After careful study of the slaking characteristics of several kinds of typical soft rock formations in soft zones such as faults. It is indicated that the soft rock is a kind of rock with the property of highly absorbing water, and facilitates argillization, softening, and slaking after that process. Using a circulated slaking experiment, it is easy to draw the conclusion that the degree of slaking is highly related to the rate of the nature of the clay in the soft rock and times of the slaking. At the same time, according to the degree of the slaking and shape of the slaking substance, the slaking process can be divided into 5 kinds of failure style. The research has also provided for the further discussion about the slaking mechanisms. The research achievement can be used as the new instructional method in the study of similar soft rock on engineered slopes.

Résumé: La roche souple se répartit vastement dans le talus des travaux. On peut distinquer la roche argileuse, le schiste charbonneux, la batture, la pelite et la roche arénacée. La caractère du développement, de la distribution dimentionnelle et orientalle et du vêlage de la roche souple influence directement à la stabilité du talus et sa conception de soutènement. Après avoir étudié la caractère typique du vêlage de la roche souple de la faille F_3, L_9, L_{10}, L_c, L_{11}, on a obtenu que la roche souple est facile de la reprise d'humidité, de l'argillisation, de l'adoucissement et du vêlage. D'après l'essai de circulation du vêlage, on a trouvé que le niveau du vêlage de roche souple a une bonne relation avec la quantité argilleuse et le nombre du vêlage. Selon le niveau du vêlage et la forme des matières de vêlage, on a fait l'analyse qualitatif pour la roche souple. On a trouvé les formes de vêlage du type V et le sabotage de 5 types des vêlages. Et puis, on a fétudié profondement le mécanisme du vêlage. Le résultat fournit une nouvelle orientation pour rechercher le vêlage du talus de la roche souple des travaux.

Keywords: collapse, discontinuities, fractures, index tests, sediments, shale, slope stability, soft rock

INTRODUCTION

The hydrophilic engineering is located in Shajinba section at upstream of Minjiang river, and it is noted for omnipotent works in this area including irrigation, generating electricity, controlling flood, balancing ecology, breeding aquatics, tourism etc. The total capability of hydropower station is 760,000 kw, and it could generate 3.427 billion kw·h electricity every year. The type of dam is plane rock-refilled dam that is 156m high. The altitude of impounding is 877m in normal condition, and the whole capability of reservoir is 1.112 billion m^3.

The engineering area is sited at relative stable place between two major faults in NE direction. It belongs to middle eroded tectonic denudation lower-relief terrain, and the strike of mountain is NE-SW which is almost along with tectonic line. Because it is controlled both by rock character and geologic structure, 180°meander has been formed at Shajinba section, and the belt-like ridge at right bank of river is surround by meander. The bedrock in construction field can be identified to shale or sandstone with coal in Xujiahe formation upper Triassic, and the main geologic structure in strata is known as Shajinba syncline. Its strike is N50°~60°E, and dip is 25°~35° in NE direction. However, the NW limb is relative steep with an orientation of N25°E/SE dipping 60°~70°, and SE limb is quite gentle with the orientation of N45°~60°E/NW, dipping 45°~60°.

The soft rock is widely spread in the engineering zone, and those soft rocks which are close related with stability of excavated slope are in the crushed belts of the major faults.

The crushed belts are widely spread in large scale and controlled by Shajinba syncline in dimension, and the attitudes of crushed belts are usually parallel with strata besides exceptions in some places. The crushed belts distributed in engineering zone can be classified into 4 different petrofabrics as argillized seams, coal, carbonaceous shale and pelitic siltstone. The shearing crushed belts in the engineering zone are characterized by broken rock, destroyed original structure, as well as low integrity and anti-weathering & mechanical capability. The soft rocks are highly sensitive to water, and the property of slaking, demineralization, and low permeability deteriorated by the property of easily absorbing water. After absorbing water, the volume will increase, and the strength & stiffness will decrease dramatically (demineralization), and even caused slaking and agrillization (Xie-xing Liao, 1995). Those unsatisfied physical and geological phenomena of those soft rocks increased difficulties of construction in certain degree, and serious influenced the stability of engineering slope. Therefore, study on hydrophilic property of soft rocks is quite critical to the engineering construction (Run-qiu Huang, et al 1991).

SLAKING TESTS ON SOFT ROCKS

The hydrophilic property of soft rocks means the changes of certain properties of soft rocks after they come across to water. The slaking of soft rocks means the capability of anti-slaking and anti-demineralization after experienced circles of wet and dry. It is clearly announced in Code for Geo-technical Investigation that the rocks belonged to level IV and V, the special characteristics such as demineralization, expansibility, and slaking should be took into consideration (Construction Ministry of P.R. China, 2002).

The soft rocks with loose structure and hydrophilic clay minerals are very easy to slake in the water. According to the slaking test, a series of slaking coefficient such as slaking quantity, slaking degree, slaking time, and slaking condition will be recorded.

Based on specifications for rock tests in water conservancy and hydroelectric engineering (Water Resources Ministry of P.R. China, 2001), the equipment and layouts of test is set up and carried out by ourselves. The types of slaking test are mainly focused on still water slaking test (similar to saturation test), and soft rocks of same petrofabric in different part of engineering zone have been chosen as samples in same team. Because it is not very regular, the samples should be pre-treated and fully specified.

The saturated time for each team is 48h (Ministry of Geology and Mines of P.R. China, 1988)•and before the test, first weight in the dry weight (W_d) of samples, then record first slaking time and fully specify slaking phenomena, meanwhile, record slaking process at any time (Table 1). At last, take out the sediments which have not been slaked (left on 4×4mm^2 gridiron), and one circle of the slaking degree S (Water Resources Ministry of P.R. China, 2001) can be easily calculated:

$$S = \frac{W_d - W_1}{W_d} \times 100\%$$

In order to study more on soft rocks, it is quite critical to do circular slaking tests on different petrofabric. Every time, it takes 48h as the circular time, and it takes the unslaked sediments from last time to do circular slaking test. There is no need to do circular slaking tests for the carbonaceous shale and agrillized seams because they have been almost fully slaked at the first time.

Table 1. Recording of the slaking process.

No.	Description of first Slaking	Description of Whole Slaking Process
2#-1	There are big fragments off and air bubbles floating on the surface after 10 min., and four obvious cracks on sample after 20 min.	The original cracks continue to enlarge to 0.3cm in 2h~6h, and the phenomena of alligator cracks become more obvious at surface. The spilled object is in fragment shape, and height of the sample decreased about 0.4cm. After 12h, the spilling along the bedding becomes dominant, and as soon as free surface forms, the fragments will fall down along bedding to free surface. The saturation coefficient is 0.13. After 48h, the mud covered on surface become thicker, and there are 60 gravels and some fragments in different shapes left on the grid.
6#-1	2 min. after having been put in water, it has been soon slaked into mud with fast speed. During the slaking, there are also boo-boo voice and soon a muddiness in the water.	After 2h~6h, the integrity has total lost its shape at all and become mud. The water becomes muddy, there are large amount of fragments floating on surface of water. After 24h the water is still quite muddy, but the sample can be clear distinguished. Scale of slaking sediments has been enlarged and the thickness has been decreased, and it looks like mud-shape at surface. There are also some big fragments, and the agglutination, which about 30% of total, has not been completely slaked. After 48h there are 68 air bubbles on the surface, and the sediments is in loose structure, which composed of 20% scale-like fragments as well as 80% rock debris and can be considered as completely slaking. After screening, the gravels left on the grid are totally 65, and quite average in shapes.
2#-2	In first 2 min., there are a lot of air bubbles produced and little coal debris left on the water surface.	The slaking is not quite obvious in the first and second time of slaking test. However, the cracks have the tendency to grow at the second time, and at the third slaking circle, the cracks continue to grow and go on happening but not completely.
2#-3	In first 2 min., there are air bubbles floating to surface, and then no air bubbles floating up any more.	After 2h~6h, the cleavage enlarged as feather-like, and the water is quite clear. After 12h~48h, there are no big differences in slaking test. The obvious cracks can be inserted a needle (approximately 0.3cm deep). There are cracks emerged around needle inserting point, and one of plant fossils broken off. With little fragment comes from the original part siltstone, the left part is very integrity and cannot be slaked at all.
2#-4	Slaking right after being put into water.	Quickly slaking with big air bubbles vertical towards the surface as well as attached on surface of the sample. Then, the rock debris around quickly sunk to the bottom and makes water muddy, and most slaked sediments are mud. During process of slaking, the fissure inside expose to water, so bubbles continues coming out, and it forms the phenomena of slaking as well as bubbling. When the fissures are filled with water, the water splitting makes the slaking faster. As the test going on, the slaking process reached peak in 6 min., and became skirt-shape in 10 min.. All the slaking sediments are mud. After 30 min. the water became muddy, and there are still air bubbles floating on the surface. Like fireworks, it forms underwater mudflow, and it also indicates the slaking is still going on in fast speed with big air bubbles and large sound. The water is muddy for long time because of the slaking.
6#-4	Slaking right after being put into water.	There is obvious slaking in 1 min., and 1.5cm depth of it has been demineralized. There are also coal debris and mud films on surface of water. After 3 min., there are some large bubbles pumping out like spring and some mud–like material alone with it. After 7 min., there are also bubbles coming out, and it suggested slaking is still continuing. 10 min. latter, more debris and other material float on the surface of water. 20 min. latter it slaked completely.

PRINCIPLE ANALYSIS OF SLAKING ON SOFT ROCK

The demineralization of rock means the deteriorating of mechanical property after it comes across to water. The anti-demineralization capability mainly counts on the proportion of hydrophilic and soluble mineral and development of fissures in the soft rocks. The more hydrophilic and soluble mineral the rock has and fissures develop, the easier it is slaked or demineralized in the water (Xiao-jia Zhu, 1996).

From the result of X-ray diffraction test on agrillized seams developed on engineering slope, it is suggested that the main ingredients of them are clay mineral (about 84~92%), and others are quartz, feldspar, and calcite. Meanwhile, as the description mentioned in Table 1, most soft rocks are full of fissures. Because the clay minerals such as illite and kaoillite are very small and highly hydrophilic (De-Fang Kong, 1991) so when water insert into the rock from the fissures, the absorption water film will become thick, and cause uneven expansion. Because of that, there is uneven stress concentrating inside of the rock, and moreover, part of agglutination will be diluted, emolliated, and dissolved, then at last be slaked and deminerilized.

Relationships between Proportion of Agrillized material and Property of Slaking.

The development, enlargement, slaking and demineralization of fissures in mudstone, which have large proportion of agrillized material, closely relate to composition of soft rocks and development of tiny structures and fissures. Therefore, the slaking and demineralization are the reflection of tiny fractures and tiny fissures. According to geologic identification and analysis, several typical clay minerals in petrofabric have been determined, and also the relationship curve between W_m(proportion of clay material) and S (slaking degree) has been drafted out. (Figure 1). From the Figure 1, it is suggested that different proportion of clay material corresponds with different slaking degree. The proportion of clay material decreases from agrillized seams, carbonaceous shale, pelitic siltstone, and the slaking degree also descends along it. So the slaking of agrillized seams and carbonaceous shale is very obvious and fast.

At the same time, from the Figure 1, the decreasing of clay material in agrillized seams, carbonaceous shale, and pelitic siltstone makes differentiation of property of slaking. It is implied that the proportion of mud also affects the property of slaking.

The slaking test also indicates that the soft rocks in engineering zone have characteristic of being permeated by water through the fissures and bedding (De-Xin Nie, 1999) (Table 1). However, the proportion of clay material has larger influence than those fissures (Figure 1).

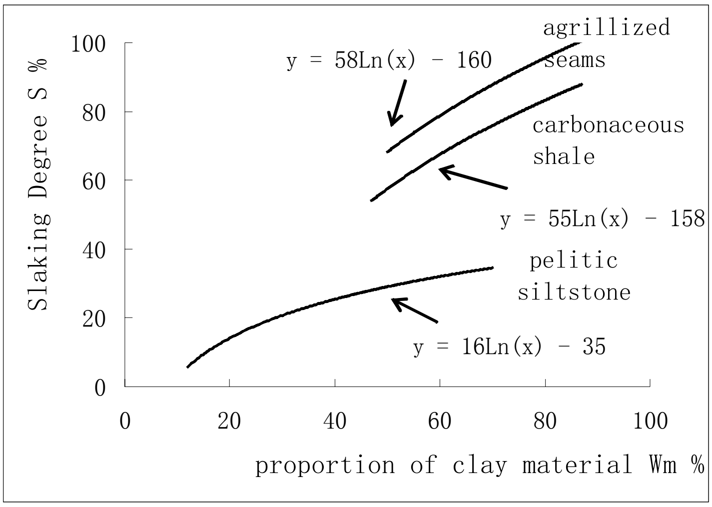


Figure 1. Curves of the degree of slaking affected by ratio of clay material

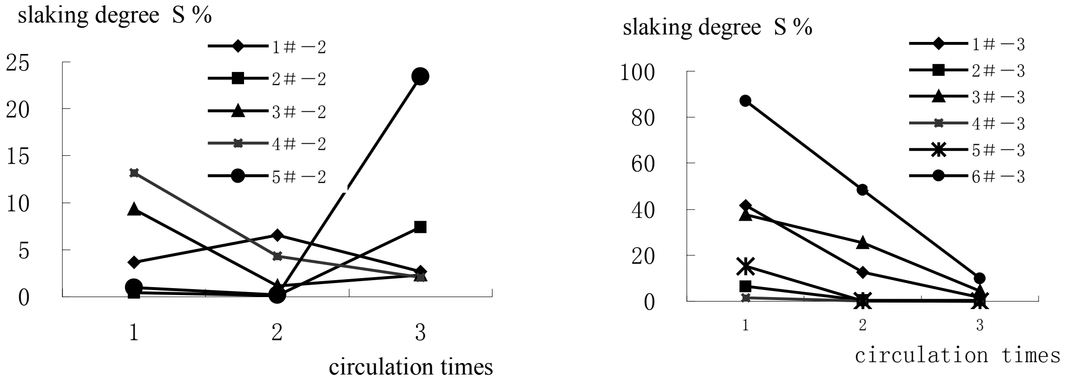
Relationship between Times of Circular Slaking and Property of Slaking

The test in China suggests that the original structure (including natural water ratio) will not be agrillized inside but only surface after submerged by water, and the large scale of slaking will not occur. But when original texture and structure of sample has been broken or disturbed, the situation will be quite different, For instance, being dehydrated or dried sample will soon began to slake when it come across to water.

After several times circular slaking, the relationship between slaking degree and circular times can be understood. The carbonaceous shale and agrillized seams have already been 100% slaking (the total volume of left debris is less than 3/4 of original sample), and the slaked sediments are made up of gravels in different sizes. After the slaking test finished, taking the stable slaked sediments for analysis, the rocks with different characteristics and size has been found from original one. The remained material of carbonaceous shale and agrillized seams are very small and average, and it can be regard as earth-like material transformed from rocks, and it cannot participate in circular slaked but only once. However, the particle diameter of pelitic siltstone is relative large. Therefore, the different sizes of slaked sediments indicated different slaking property in different petrofabrics.

From the relationship of Figure 2(a), after experienced twice circular slaking, the slaking degrees of coal petrofabrics (except for sample $1^{\#}$-2) have the tendency to descend (descended 4.525%). After third time slaking test, except for $2^{\#}$-2 & $5^{\#}$-2 obvious increased and $3^{\#}$-2 increased slightly, others all decrease, but not dramatically (3.1%). It is also possible that the unslaked material in first two times slaking tests reached slaking period in third times in $2^{\#}$ and $5^{\#}$, and it is also indicated that the coal will be circularly slaked in different degree of the alterative environment of dry and wet.

When the first time saturated sample $1^{\#}$-2, the phenomena of slaking is not very obvious, and there is only little debris off and colluvial deposit sunk to bottom of water. During the second time of circular slaking, the cracks on the sample are obviously enlarged and little debris off and colluvial deposit sunk to bottom of water. The slaking is still not very obvious, when the third time circular slaking test happened, and there are some air bubbles attached at surface of sample. The conclusion can be drawn about coal that the slaking capability of the rock is not very well, because there is no serious slaking even in dramatically changes of condition.



a. Circular Slaking Test of Coal　　b. Circular Slaking Test of Pelitic siltstone

Figure 2. Times of the circulated slaking and relationship curves a. Circulated slaking experiments of coal b. Circulated slaking experiments of pelitic siltstone

The geologic identification under microscope is suggested that the sample $2^{\#}$-2 is the muddy coal in shape of compaction and no cracks on it. During the formation of coal, there are also some material in continental facies, such as mica, silt involved in. the test mentioned above indicated that the capability of slaking is also not very well, and in another word, the agglutination is quite good. More specific explanation is that the coal which is made up of organic content is difficult to slake because the organic material is usually anti-hydrophilic.

The geologic identification under microscope suggested that the sample $5^{\#}$-2 is dolomitic-mud silt mudstone and metamorphic lamina carbonaceous shale, and 80% is agrillized seams, 15% is siltstone, 5% is coal debris and other organic material. After circular changes between dry and wet, the slaking will be more obvious when it come across water again. At beginning of slaking test, there are cracks at surface of sample, but it has not reached the condition of slaking. However, after it has been circulated for many times, the cracks gradually enlarged and the mud which increased inside began to argillize, at last the obvious slaking phenomena occurs. Meanwhile, from the phenomena of slaking, during third times slaking test, there are always mud film floating on the surface of water, and the water is always muddy, too. The clay material which also belongs to slaked sediments is the unrecyclable part of amount in the circular slaking test.

From Figure 2 (b), after 3 times circular slaking test, the slaking degree of all the sample have the tendency of decreasing, and with more slaking circles, the slaking degree has not shown any sign of obvious rebound either. It indicated that the sample has already completely slaked. It is already known in the description above that the first slaking is not very obvious and slaking is very slowly, just implied from air bubbles floating to surface and cracks growing. The longer will the sample be saturated under water, the larger cracks will grow, then the rock and coal debris begin to slaking when come across to water, but most of them remained on surface of water, at the same time, there are a few little blocks separated from original rock and sunk to the bottom. The second time slaking is the unslaked material of first time. It is relative integrate and less cracks, and the phenomena of slaking is not so clear. In the third time slaking test•the unslaked material are more integrate and almost no cracks left on it, so the phenomena of slaking almost can not been seen. Thus, the conclusion can be drawn that the slaking property of pelitic siltstone is not very well.

The identification under the microscope believes that sample $3^{\#}$-3 is belt-like pelitic mudstone, $6^{\#}$-3 is muddy siltstone, with more mud. However, after 3 times slaking circulation, the slaking degree decreased dramatically. It can be indicated that the proportion of mud is predominant in its composition. At the first time of slaking, the mud has almost been completely agrillized, and inside pelitic siltstone is hard to form slaking in large scale.

PATTERNS OF SLAKING

According to study on classification principle, slaking phenomena, slaking condition, and slaking index of soft rocks (Liu Chang-Wu, 2000), the basic principle of classification patterns of soft rocks is indicated as follow.

Table 2. Classification of slaking rocks

Soft Rocks Property	I	II	III	IV	V
Slaking Degree	<5%	5~10%	10~50%	50~100%	100%
Slaking Property	Stable with the time goes on, almost not slaking.	Slaking is not obvious, only a little part of it has been slaked.	Phenomena is not obvious, little has been slaked.	The phenomena of slaking are quite obvious.	Completely slaked in short time, and phenomena is quit obvious.

1 It is advised to classify saturated and slaked soft rocks into 5 types based on slaking degree and slaking phenomena of the tests (Table 2).

2 According to the shapes of slaked sediments (Man-Chao He, 2004), there are 5 different types of the failure patterns in saturated soft rocks: a, mud-like failure. b, debris-like failure, particle diameter of debris 1~5mm. c, brecciaed-like failure, the particle diameter of brecciaed 5~10mm. d, shiver-like failure, particle diameter of it >10mm. e, saturated failure, not fail.

Based on slaking pattern mentioned above, the synthetic classification and scale of slaking of soft rocks with different characteristics could be indicated in Table 3.

From Table 3, it can be simply understood that the carbonaceous shale and agrillized seams are easy to slake and belongs to class a(14.29%).Those soft rocks will quickly slake after come across to water, and the water absorption ratio will dramatically increased and surpass the liquid limited. The original strength of rock will be complete lost, and it belongs to extremely unstable expansion soft rocks. The slaking property of pelitic siltstone and coal are relatively weak, and they belong to class b(33.33%), c(19.05%), d(33.33%). When interacting with water, it usually happen mechanical failure, also named physical disintegration, but the rock debris is still integrated. As far as the total slope concerned, the soft rocks are very unstable because it will expanse after come across to water. Obviously, the leading types of slaking material in the slope are type b and type d, about 2/3 of total. Besides to prevent sliding of slope, the specially supporting on b and d types of soft rocks should be alerted.

Systematical analysis on the tests above, when the soft rocks have been resaturated into water after they have been dried, or under circulation of alternative from dry to wet, it is easy to be slaked, and during the slaking the chemical composition have not been changed, but the strength has been dramatically decreased just like weathering except completed in short time. Particularly carbonaceous shale and agrillized seams petrofabric•they all have been slaked to "earth-like" at last. The longer the slaking lasted, the more completely it slaked.

CONCLUSIONS

After study at soft rocks at different of engineering areas, a few conclusions can be drawn and suggested below.

(1) Soft rocks are easy to absorb water and agrallized, demineralized, and slaked. It can be regard as macro-reflection of micro-identification.

(2) The petrofabric of carbonaceous shale and agrillized seams are easy to be slaked, and slaking degree is 100%. Both of them have been completely slaked at the first time, and there is no need to do circular slaking tests.

(3) The proportion of clay material in soft rocks is quite critical to slaking of soft rocks. With decreasing of proportion of them in agrillized seams, carbonaceous shale, pelitic siltstone, the capability of slaking has been descended. It also means that the proportion of clay material directly influenced slaking capability.

(4) After several times of slaking circulation, the relationship between degree of slaking and time of circulation can be known. Take the coal and petilic siltstone for example, after experienced 2~3 times of circulation slaking tests, the slaking degrees of all the samples have the tendency to decrease. It is also suggested that under the alternative environment of dry and wet, the circulation slaking in different degree will occur.

(5) Based on slaking degrees and failure patterns of slaking, the soft rocks can be classified into 5 different types, and leading failure patterns in engineering zone is type b and d, in total 2/3.

Table 3. Synthetic slaking experiment of soft rocks in engineering area

No.	Rock Character	Slaking Degree S(%)	Time of circulation	Classification
1#-1	Belt-like pelitic mudstone (mudy shale)	100	1	V, c
2#-1	Belt-like coal debris with hydromica muddy shale	65.9	1	IV, c
3#-1	***Belt-like pelitic mudstone***	10.3~37.2	2	III, d
5#-1	***Dolomitic pelitic mudstone***	0.87~0.04	2	I, d
6#-1	Coal debris pelitic mudstone	100	1	V, c
1#-2	Peat-coal	3.6~6.5~2.6	3	I~II, b
2#-2	Mud-coal	0.4~0.1~7.3	3	I~II, b
3#-2	Belt-like coal debris with hydromica muddy shale	9.3~1.1~2.2	3	I~II, b
4#-2	Peat-coal	13.2~4.3~2.0	3	I~III, b
5#-2	Dolomitic-mud silt mudstone and metamorphic lamina carbonaceous shale	0.9~0.2~3.4	3	I, b
1#-3	Calcium muddy siltstone	41.7~12.5~1.7	3	I~III, d
2#-3	Dolomitic siltstone	6.6~0.4~0.3	3	I~II, d
3#-3	***Belt-like pelitic mudstone***	37.6~25.5~4.5	3	I~III, d
4#-3	Middle shape sandstone with fine debris	1.5~0.2~0.01	3	I, d
5#-3	***Dolomitic pelitic mudstone***	15.3~0.1~0.07	3	I~III, d
6#-3	***Pelitic mudstone***	86.9~48.4~9.9	3	III~IV, c
1#-4	***Belt-like pelitic mudstone***	100	1	V, b
2#-4	***Dolomitic-mud silt mudstone and metamorphic lamina carbonaceous shale***	100	1	V, a
4#-4	Schisted uneven debris sandstone	100	1	V, b
5#-4	Fine-debris mudstone	62.2	1	IV, a
6#-4	Metamorphic lamina carbonaceous shale	100	1	V, a

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