

Restoring Storage Capacity at Roseau Reservoir following Hurricane Tomas

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SYNOPSIS. On 30 October 2010 Hurricane Tomas passed over the island of St. Lucia causing significant damage to the Roseau Dam. The dam is a 40m high Concrete Faced Rockfill Dam (CFRD) constructed between 1993 and 1995 and is owned and operated by the Government of St Lucia, Water & Sewerage Company Inc. (WASCO). The peak reservoir level in Hurricane Tomas is not known, however there are indications which suggest that the peak level would have been at least 3.35m above the spillway crest level - equivalent to a peak discharge of 293m³/s (about 100 years return period).

In early 2011 Halcrow engineers carried out site inspections and commissioned a bathymetric survey, sediment sampling and testing. A comprehensive report detailing the assessments carried out and recommendations for remedial works was prepared and submitted to the Government of St. Lucia for consideration and approval.

This paper discusses the catastrophic impact of hurricane forces on a small dam, in particular the siltation problem and works necessary to help restore the storage capacity in the reservoir. The case study also demonstrates that siltation in the reservoir, which is normally perceived as a long term problem, can be extensive in a relatively short period under extreme forces and that reservoir flushing, which is the preferred way of managing siltation in reservoirs, may not be practical for Roseau Reservoir.

CURRENT STORAGE CAPACITY

Bathymetric survey

Following the hurricane a bathymetric survey was commissioned to determine the storage capacity and current state of sediment deposition at Roseau Reservoir. An earlier (2005) survey was repeated, with bed profiles measured at 50m intervals across the reservoir along the entire reservoir length. In the area immediately upstream of the dam the bed profiles were measured at a reduced interval of 25m. In order to provide better accuracy in the vicinity of the dam, bed profiles perpendicular to the dam were also obtained every 15m. The survey was completed with a longitudinal profile

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of the entire reservoir, following approximately the original thalweg of the 2005 survey. Figure 1 shows the alignments and plan view of the reservoir area which was surveyed. The recent bathymetric survey revealed that approximately 400m of the reservoir backwater region (chainage 1.4km to 1.8km) which was accessible in the 2005 survey was now completely silted up.

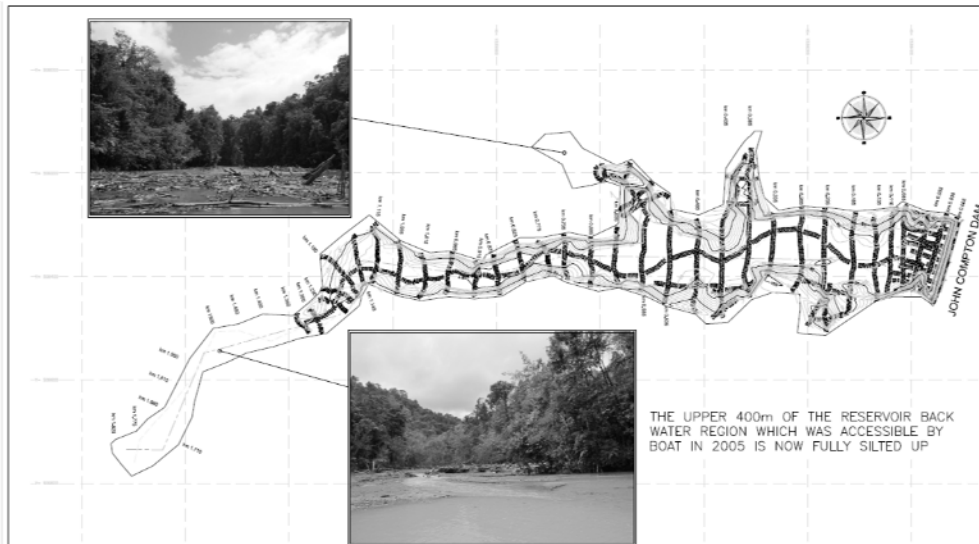


Figure 1. Plan view of the surveyed area of the reservoir

Existing storage capacity and storage loss since 2005

The survey showed that at full reservoir level (spillway level at 101.5mASL), the reservoir storage capacity has been reduced from approximately 2.8Mm³ to 1.9Mm³, representing a loss of about 32% since 2005. It is unclear what the storage loss was compared to the original reservoir capacity as the survey at impoundment has never been located. There is, however, a record indicating that the original design capacity was 3Mm³, thus making the storage loss to date approximately 35%.

The 2005 bed profiles showed a natural siltation gradient profile where larger particles are deposited in the upstream backwater region and only the finer material is carried into the deeper body of the reservoir. The recent survey showed a relatively flat bed profile at around 87mASL covering almost the entire reservoir length, which suggests the sedimentation rate is not progressive but heavily influenced by the extreme flood event which carried the previously deposited sediment delta in the upper backwater region into the deeper section of the reservoir.

The progressive siltation rate in the coming years at this reservoir cannot be determined accurately due to lack of sediment yield data, as the amount of incoming sediment is not being monitored. However there has been a suggestion by others in a past report that sediment yield, as estimated from

an empirical formula, could be $8600\text{m}^3/\text{year}$. It is understood that the catchment area is stable with very limited human activities, but there is evidence of an unstable reservoir rim where at least thirty landslides were observed in the catchment area by an aerial survey shortly after Hurricane Tomas. It is very likely that the sediment already deposited in the backwater region will be carried further into the deeper region of the reservoir in the next extreme flood event, thus reducing further the storage capacity of the reservoir.

The current bed level at 87mASL blocked the lower intake draw off located at 82mASL and the bottom outlet pipe, the invert level of which is estimated to be at 67mASL . It has been reported that since the hurricane unsuccessful attempts have been made to operate the riparian outlet which is branched off from the bottom outlet pipe. It appears that the bottom outlet pipe (which passes through a concrete plug in the diversion tunnel) is blocked with silt at its upstream end. A diver survey carried out in February 2011 confirmed these blockages.

A representative cross section showing the bed profiles along the thalweg and a summary of storage capacities between the surveys is presented in Figure 2.

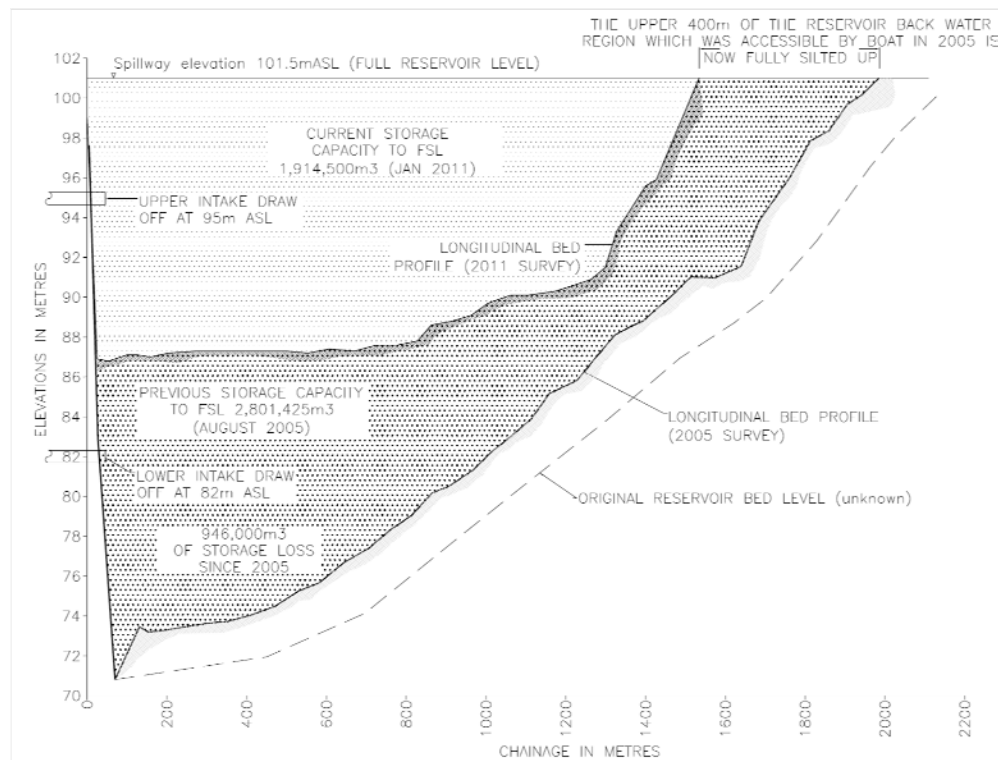


Figure 2. Bed profiles along the thalweg and storage capacities between the 2005 and 2011 surveys

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As indicated, about 887,000m³ of storage has been lost to siltation in just over five years, although it is suspected that the majority of the sediment was transported in the single recent hurricane event. The reservoir current bed level is only about 14.5m below the Full Supply Level (FSL) in the first kilometre from the dam, thereafter rising sharply to FSL near the backwater region.

ADDITIONAL STORAGE CAPACITY TO BE PROVIDED / RESTORED

Analysis of the bathymetric survey results showed that the deposited sediment is not uniformly distributed in the reservoir and can be roughly apportioned to the following: Zone A 146,773m³; Zone B 362,478m³; 188,175m³ within the siltation fringe and the rest in the dead storage or inactive zones as shown below in Figure 3.

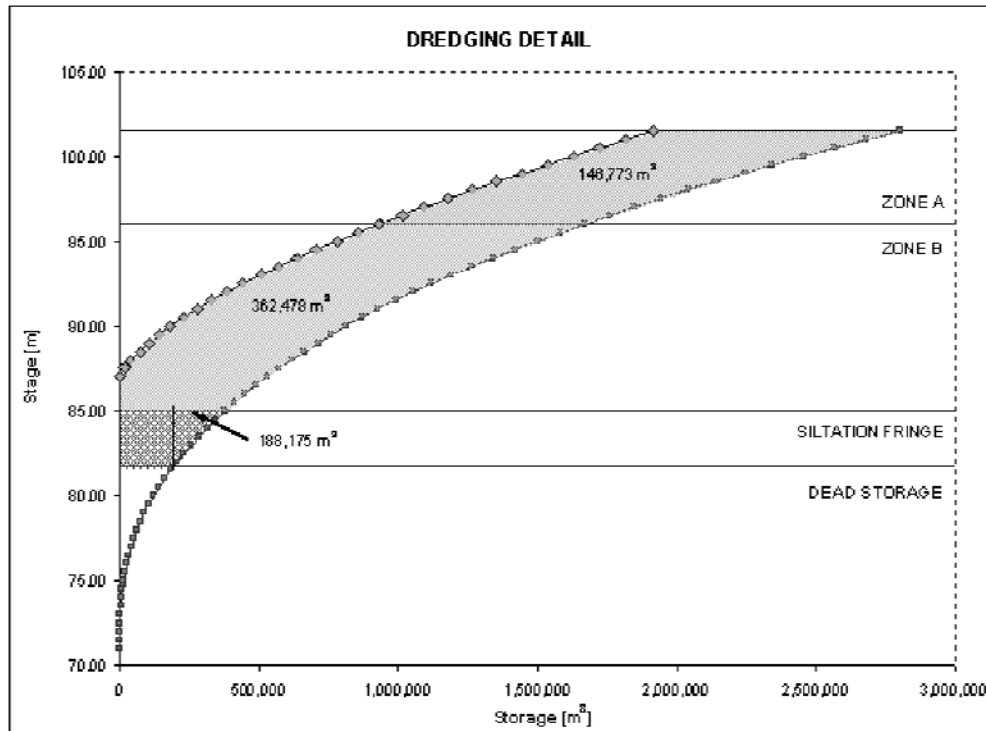


Figure 3. Distribution of deposited sediment since 2005

A study of the conjunctive use of the Roseau Reservoir and the Millet intake (in the adjacent catchment) to meet various water demand scenarios showed that the desired draw-off of 45MI/d cannot be achieved with high reliability. Since 2005 the reservoir storage capacity has been depleted by about 886,925m³ making the existing storage even more inadequate to meet the required draw-off, especially during the dry season. In order to meet new draw-off demand, besides the mitigation work to restore the storage capacity, there is a plan to install Obermeyer spillway gates on the spillway crest in order to raise the water level in Roseau Reservoir by 3m.

Table 1. Key volumes

Item	Volume (m³)
Sediment deposition since 2005	886,925
Zones A and B only ^a	509,251
Zones A, B and siltation fringe	697,427
Current (2011) storage capacity	1,914,500
Storage capacity with +3m (higher spillway crest) ^b	2,515,975
Storage capacity at 2005	2,801,425
Target storage capacity (original storage capacity)	3,000,000
Active capacity after dredging ^(a+b)	3,025,226

A water resources study revealed that the sustainable draw-off at this reservoir has not been significantly affected by the sedimentation since 2005. Most of the water drawn from the reservoir is obtained from Zone A, thus the recent storage loss in Zone B and beyond has only nominal impact on the current draw-off capacity. However providing additional storage of about 600,000m³ by raising the spillway crest level alone is insufficient to replace the storage loss due to siltation since 2005.

Storage in active Zone B may not have influenced the existing draw-off capacity, however further deterioration of storage through progressive siltation will affect water availability and future draw-off capacity from the reservoir, especially in the case of a prolonged drought. Restoring capacity in Zone B would extend the useful life of the reservoir.

In order to meet higher draw-off capacity with good reliability and to cater for progressive siltation in the reservoir, it is expected that storage beyond the 2005 capacity of 2.9Mm³ will be required. It was accepted that effort should be made to achieve the original storage at impoundment of 3Mm³. This could be achieved by providing 600,000m³ from raising the spillway crest and the rest by restoring lost storage by means of dredging or flushing.

The volume of dredging to:

- 1) restore the storage to meet the 2005 water draw-off demands (in addition to the 600,000m³ of storage provided by heightening the spillway crest level) is estimated to be 146,773m³ in active Zone A
- 2) restore active Zone B in order to extend useful life and provide storage for progressive siltation is estimated to be 362,478m³.

It is anticipated that restoring the storage loss in the siltation fringe is uneconomical as the cost of dredging beyond 15m increases significantly

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and the benefit of restoring the storage here is unclear, as it has no impact on the draw-off capacity.

OPTIONS OF DESILTING MEASURES AT ROSEAU RESERVOIR

No dredging and no flushing

This represents the 'do nothing' option where sediment build-up is allowed in the reservoir with no effort made to alleviate the problem. Current sediment deposition has reached 87mASL at the dam face. This is 14.5m below the current spillway crest level and 20m above the bottom outlet draw off. The progressive siltation rate at this reservoir cannot be accurately determined due to lack of sediment yield data. It is, however, very likely that the sediment delta deposited in the backwater region will be carried further into the deeper region of the reservoir in the next extreme flood event, thus reducing further the storage capacity and threatening the useful life of the reservoir.

Due to the relatively small reservoir storage capacity, the 'do nothing' option in this reservoir will see further deterioration of storage capacity. Depleted live storage will also promote a higher level of sediment concentration entering the draw-off intake, requiring treatment of the higher turbidity. Blockage of the draw-off intake may also seriously disrupt water abstraction to the treatment plant.

Reservoir flushing (via existing bottom outlet pipe)

Experience has shown that the success of pressurised flushing, where the water level is not drawn down, is limited. An evaluation of reservoir flushing shows that the flushing efficiency at Roseau Reservoir would be limited. It has been estimated that without other mitigation measures, for example dredging works to restore the storage capacity prior to carrying out periodic reservoir flushing, only a limited proportion of the storage can be maintained in the long term (less than 10% of the original capacity).

Criterion	Indicator of successful flushing	Condition estimated for Roseau Reservoir
Drawdown ratio, DDR, measure the possibility of flushing sediments from outlets close to the initial bed level upstream of the dam.	DDR > 0.7	0.16
Sediment Balance ratio with Full Drawdown, SBR _d , measure of the proportion of the incoming sediments which may be flushed from the reservoir.	SBR _d > 1	16

Criterion	Indicator of successful flushing	Condition estimated for Roseau Reservoir
Flushing width ratio, FWR, check if the reservoir could be too narrow for the natural width of the flushing channel to develop during flushing.	$FWR > 1$	1.2
Top width ratio, TWR, investigate if sediment will remain along the perimeter of the incised flushing channel.	$TWR > 1$	0.31

The viability of flushing at Roseau Reservoir in the long term has been assessed assuming that storage capacity has been restored to the 2005 capacity. The 2005 storage capacity was selected because the storage capacity and reservoir bed profile at impoundment have never been established.

Assuming a flushing discharge of $5.45\text{m}^3/\text{s}$ is available through the bottom outlet pipe (assuming the pipe is in good working condition), a sediment flushing rate of $0.41\text{t}/\text{s}$ has been estimated using the Tsinghua University approach. Thus the total sediment that can be flushed in 24 hours is estimated to be 35,424t or about $23,600\text{m}^3$ (assuming a sediment density of $1500\text{kg}/\text{m}^3$). This is nearly the entire gross storage capacity to 76mASL. If water is drawn down to the allowable minimum reservoir operation level at 96mASL for flushing, it will take approximately 11 days for the reservoir to refill to Full Reservoir Level (FRL) with an average inflow at the onset of the flood season of $1.25\text{m}^3/\text{s}$.

With reservoir flushing carried out during the wet season when high inflow rates are available, $23,600\text{m}^3$ of gross storage capacity may be maintained at this reservoir (assuming recharge rates beyond 11 days is unacceptable). However sediment will remain along the perimeter of the incised flushing channel. Only 30% of the storage capacity is considered as sustainable storage. There is also a high probability of sediment build up in front of the intake draw-offs should there be long period between flushing operations.

Flushing through the diversion tunnel

The idea of utilising the existing diversion tunnel to route flood discharge and sediment load around the reservoir into the downstream river channel during the flood season has been investigated. During floods the gate is opened and sediment-laden water is diverted to the downstream end. This flushes the sediment from the reach upstream of the bypass tunnel and reduces the sedimentation rate in the reach between the diversion tunnel

DAMS: ENGINEERING IN A SOCIAL & ENVIRONMENTAL CONTEXT

intake and the dam. When the reservoir water level is drawn down to initiate flushing, previously deposited sediment is re-agitated and sediment deposited further upstream can be drawn into the diversion tunnel.

A higher flushing capacity can be achieved as the flow capacity of the diversion tunnel is larger than the bottom outlet pipe. However there has been a recent suggestion that the tunnel roof may have collapsed due to the presence of sink holes along the tunnel alignment. Assuming that the tunnel has not been damaged in the recent hurricane, the restoration of the tunnel will require the concrete plug to be removed, a new gate to be installed and reinforcement of the tunnel to withstand severe abrasion.

Ideally the intake of the bypass should be located in shallow water at the upstream end of the reservoir. The existing diversion tunnel is located in the deep water and only 50m from the dam body. Although higher flushing capacity can be expected, the increase in flushing efficiency is expected to be marginal due to unfavourable topographic conditions.

Furthermore the cost of making the bypass tunnel suitable for transferring sediment-laden flow may be prohibitive and flushing efficiency is limited due to the restriction to draw-down water level at this reservoir.

Dredging at Roseau Reservoir

An assessment of the current state of siltation in the reservoir and the dam bottom outlet feature together with the operational constraints quickly revealed that flushing alone is ineffective and would not restore a significant storage capacity at this reservoir. The limited flushing capacity of the bottom outlet and restriction in lowering water level in the reservoir are the main reasons effective flushing cannot be achieved at this reservoir. Although the bottom outlet pipe invert is ideally located near the original reservoir bed level, the intake is situated about 50m away from the upstream face of the dam so deposition beyond this point can never be removed by means of flushing.

In view of the dam operational restrictions and topographic conditions, dredging is considered practicable at Roseau Reservoir to restore some of the storage capacity lost due to siltation and may offer a sustainable means to help maintain or extend the useful life of the reservoir. Allowing for the limitations of the various types of dredges, the hydraulic suction dredge has a clear advantage operating at Roseau Reservoir. The hydraulic suction system has relatively high production rate; does not create turbidity problems unless the dredge is very near to the intake; is able to handle a range of sediment sizes from coarse to fine material; and transferring dredge slurry in a pipeline minimises vehicular transport over land.

PROPOSED SYSTEM FOR ROSEAU RESERVOIR

As dredging is to be carried out in addition to the raising of the spillway crest, which would provide most of the storage requirement, the production rate of the dredging system becomes less significant. Since dredging works here are proposed for the long-term benefit in extending the reservoir's useful life, a smallish dredge with an average production rate that attracts low capital and maintenance costs would be ideal to help maintain the storage against siltation at Roseau Reservoir. Due to the low hydraulic gradient between the deposition level in the reservoir and the discharge level at the downstream river, a pump hydraulic suction dredging system is recommended to extract deposited sediment from the reservoir.

Localised dredging to clear the blocked lower intake and the bottom outlet is required as a matter of urgency as a higher water abstraction rate may be restricted by the blocked intake; the restoration of the blocked lower outlet is important for the safety of the dam.

There is a limited area immediately downstream of the dam which is sufficiently large to be used as containment area. A possible solution to overcome the availability of an adequate land bank to be used for the containment area is to employ a portable dewatering facility. The use of a dewatering unit may restrict the dredging production rates but the units can be doubled up to increase the dewatering rate.

PROGRAMME

Ideally dredging should be carried out prior to increasing the reservoir storage by raising the spillway crest level. The system would need to overcome technical challenges and cost increases due to the additional 3m dredging depth if dredging is carried out after the TWL is raised. There is the option of limiting dredging activities in the wet season when it is anticipated that there will be sufficient inflow sustaining the draw off requirement and the inflatable gates are lowered reducing TWL.

Given that raising of the spillway is the principal means of providing additional storage to overcome the acute storage shortfall, it is anticipated that the works to increase the crest level will take precedence. Furthermore dredging beyond active Zone A is seen as long-term strategy in extending the useful life of the reservoir, hence can be carried out over several years if required.

Using an approximate relationship between dredge size and production rate for a typical dredging system, complete dredging of Zone A (146,773m³) based on 150m³/hour dredging rates operating 12 hours each day (7 days a week), taking into account down time due to maintenance and general movements of plant, would take approximately three months. This is assuming that dredging rates are not restricted by the dewatering capacity.

DAMS: ENGINEERING IN A SOCIAL & ENVIRONMENTAL CONTEXT

Assuming that dredging works are restricted to only 6 months/ year during the wet season where there will be surplus incoming water (i.e. draw off requirements from the reservoir not affected) and that TWL can be lowered to existing level of 101.5mASL, the complete dredging of the 509,000m³ in Zones A+B will take approximately 16 months.

CONCLUSION AND RECOMMENDATIONS

The qualitative assessment shows that flushing with limited efficiency may be operated at this reservoir in the wet season to aid current density venting. However the limited capacity of the bottom outlet, restrictions in lowering water level and the requirement of a desilting basin within the downstream river make flushing operation at Roseau Reservoir unfavourable.

The desired draw-off could be conditionally achieved by a combination of raising the spillway crest to provide additional storage and dredging works to restore some storage loss due to siltation. Restoring active Zone A is required to meet the current water demand draw off. The amount of siltation in Zone A since 2005 is estimated to be at 149,000m³ from the bathymetric survey. Although the present capacity in Zone B is able to sustain current draw off demand, the storage capacity is at the threshold where any further siltation, either progressive or due to an extreme flood event, would affect water quality and abstraction rate from the reservoir. Dredging a volume of 362,000m³ is required to restore Zone B to its 2005 capacity. The amount to be dredged to maintain sustainable storage capacity once the 2005 storage is restored is dependent on the incoming sediment yield from the catchment and the trap efficiency of the reservoir.

Due to the low hydraulic gradient between the deposition level in the reservoir and the discharge level at the downstream river, a pumped hydraulic suction dredging system is recommended to extract deposited sediment from the reservoir. The proposed hydraulic suction dredging system will need to incorporate a containment area downstream of the dam where extracted slurry can be allowed to dewater and be removed periodically. Given the limitation of the operating condition, a containment facility with minimum surface area of 90,000m² is anticipated. A portable dewatering system is introduced as a feasible solution to the problem of land availability for containment area. It is estimated that dredging of Zone A will take three months. Dredging of Zones A and B would be carried out in ten months within an overall 16 month period, as dredging would only be undertaken in the wet season.

The case study at Roseau Reservoir demonstrated that siltation in a reservoir, which is normally perceived as a long term problem, can be extensive in a relatively short period under extreme forces. Provision for sufficient drawdown and flushing capacity should be present in all dams especially in dams with relatively small reservoir storage capacity.

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