Reinforced soil wall for a working platform for 1000 ton crane and TBM machine: Elan Valley Aqueduct, Bleddfa, Wales, UK

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ABSTRACT: The Elan Valley Aqueduct (EVA) rehabilitation project consists of the replacement of some sections of the existing aqueduct built over a 100 years ago, which currently supplies water to Birmingham and surrounding areas, from mid-Wales. This paper refers to one of the replacement sections of the old structure where it was required to construct a new conduit with a tunnel of 1.8km long and 3.0m diameter. For the construction of the bypass conduit, a horizontal working platform of 160m long and maximum 13.3m high was required to support the construction traffic, the 1000 ton crane to assemble the Tunnel Boring Machine (TBM) and the 150 ton TBM. The solution consisted on a Reinforced Soil Wall using Strata geogrids of 120 and 60 kN/m and on-site cohesive material as part of the cut-and-fill balance of the project. The fill material was very susceptible to weather conditions and it was required to follow a strict testing regime during the installation and compaction of each layer to ensure the stability and good performance of the structure. On top of the Reinforced Soil Wall (RSW), a granular platform was constructed using biaxial Tenax geogrids to distribute the heavy loadings. The RSW was constructed between April and June 2016 and the tunnel was successfully completed in November 2016 with the extraction of the Tunnel Boring Machine.

Keywords: Reinforced Soil Wall, on-site won material, Geogrids, working platform, cohesive fill, installation testing regime

1 INTRODUCTION

The Elan Valley Aqueduct (EVA) was built over a 100 years ago to bring water to Birmingham and surrounding areas from mid-Wales. The EVA is approximately 120 km long, discharges 300 million litres of water every day into the reservoir at Frankley Water Treatment Works (WTW) in Birmingham, and currently supplies water to about 1.2 million people. The EVA is an essential resource to supply water to Birmingham and surrounding areas and was in need of modernization and extensive refurbishment to keep it in service for the future.

Severn Trent Water launched the (BRP) project to provide an alternative source of potable water to Birmingham during the refurbishment work on EVA and in future cases of emergency. The project consists of the construction of an extra pipeline of 25 km long, upgrades to the Frankley WTW and the offline replacement of the existing aqueduct in 3 locations: Bleddfa, Nantmel and Knighton. The project described in this paper refers to the offline replacement of the existing conduit in the section located at Bleddfa, with a new conduit 1.8 km in length and 3.00m in diameter installed into a tunnel through the hillside.

For the construction of the bypass conduit, two deep shafts were designed at either end of the pipeline, to allow connection to the existing aqueduct and also to allow construction of the tunnel between the two shafts with a 150 ton Tunnel Boring Machine (TBM).

At one end of the new bypass tunnel, downstream of the project, it was necessary to construct a levelled and horizontal working area to support the construction traffic and a 1000 ton crane, which would be used to assemble the Tunnel Boring Machine (TBM) for the construction of the tunnel. For this it was proposed to construct a Reinforced Soil Wall with Stratagrids and on-site won material to surround the location of the cofferdam for the TBM launch shaft.

The length of the RSW was 160m, with a maximum height of 13.3m, a slope angle of 85 deg and 43 layers of Stratagrid spaced 300mm. A working platform was constructed, on top of the RSW, with selected granular material of 970mm thickness and 3 layers of Tenax biaxial geogrid for the reinforcement.

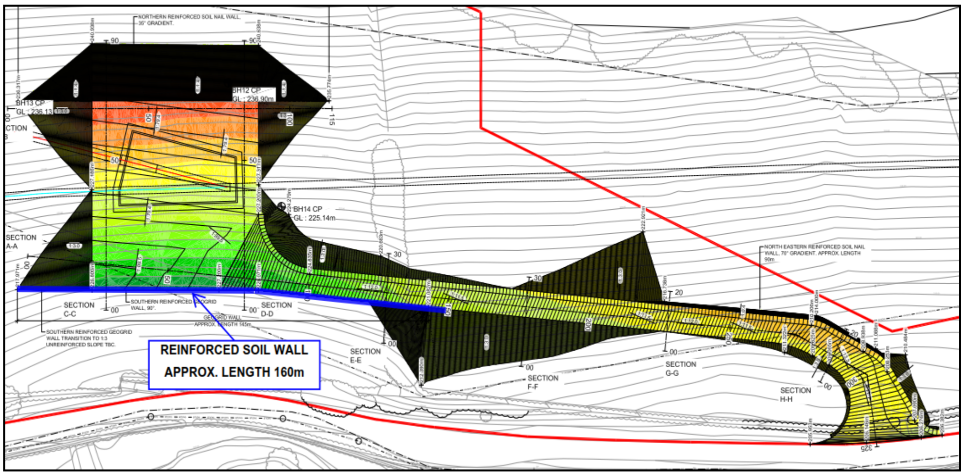

Figure 1. Plan View: Downstream EVA Bleddfa – RSW

Figure 2. Aerial View: Construction of RSW EVA Bleddfa

2 DESIGN CONSIDERATIONS

2.1 *Design Method and Standards*

The design of the Reinforced Soil Wall considered the surcharges applied on top and behind the wall, the pressure of the soil at the back and all the properties of the soils (reinforced soil, retained soil, foundation soil). The design followed the design methodology of the 'Tied back wedge analysis' used and recommended by many geotechnical engineers and geosynthetics specialists. The design was based on the Limit Equilibrium analysis for the internal and external stability of the soil-geogrid structure and global stability of the overall structure.

For the internal stability, each layer of reinforcement had to resist the horizontal pressures caused by the surcharges and the thrust of the soil, to prevent pull-out and direct sliding of each layer and prevent sliding of the whole reinforced mass. With this analysis it was possible to determine the required strength of the geogrids, the spacing and the minimum length the layers of reinforcement to meet the equilibrium for each possible failure mechanism. Once the strength, length and spacing of reinforcement were determined, it was required to check the external stability of the reinforced block against overturning, sliding and bearing capacity failure.

The global stability was performed on the overall structure including the retained soil and the foundation soil using slope stability methods such as Bishop's modified method of slices.

For the internal stability of the slopes we applied the Limit Equilibrium Analysis, with adequate selection of material properties and safety factors, according to BS8006-10 Code of practice for strengthened / reinforced soils and other fills and BS8002-15 Code of Practice for Earth Retaining Structures. Checks were made for the ultimate limit Combinations A and B and serviceability limit states Combination C.

Global stability of the Reinforced Soil Wall was analyzed in accordance with BSEN1997-1:2004 – Eurocode7, Design Approach 1 and 2.

External conditions were also considered in the design to determine the type of face and the drainage and subdrainage systems of the Reinforced Soil Wall.

2.2 *Surcharges*

One of the challenges for the design of the Reinforced Soil Wall was to find the most appropriate way to consider the loading applied by the 1000 ton mobile crane, according to the specifications of the project. To consider the surcharge we analyzed 3 different scenarios (see detail below) and for the final solution we used the results of the worst case scenario for each of following: the strength of the geogrids, the spacing between the layers and the length of reinforcement.

Another key aspect to consider in the design was the minimum distance from the crest of the wall required for the crane to move and turn in a safe way. The minimum distance was 3 meters to allow adequate space for a safe turning circle of the crane.

Based on the above, we considered a surcharge loading equivalent to a LTM 11000 DS Mobile crane and ballast load, simulating the wheels with strip loads of 0.35m wide of 178.7 kN/m offset 3.00m and 5.55m from the crest of the wall.

Figure 3. Surcharges: 1000 ton Mobile Crane and Heavy construction Traffic

The 3 scenarios of analysis for the surcharge were:

- Scenario A) surcharge of 30 kN/m2 from 0m and offset 3m from crest position according to BS8002:2015 – Code of practice for earth retaining structures. Imposed loads on vehicle traffic areas. The surcharge of 30 kN/m2 applied from the face of the wall was analysed to take into account heavy construction traffic.
- Scenario B) surcharge of 70 kN/m2 offset 3m: Modelling the strip load as 2.55m of 178.7 kN/m offset 3.0m from crest position
- Scenario C) surcharge of 43.74 kN/m2 offset 3m: Modelling the strip load using the 45 degrees distribution approach according to CIRIA C580 – Embedded retaining walls.

The length of the geogrids was determined through Scenario C) and the required strength through Scenario B). The maximum spacing between the layers of geogrid was fixed through Scenarios A) and B).

Figure 4. Tunnel Boring Machine TBM (150 ton)

2.3 *Reinforced fill properties*

One of the main objectives of the project was to achieve a cut-and-fill balance, so the design of the Reinforced Soil Wall was based from the beginning on using on-site won material, instead of importing fill material.

Based on the results of the preliminary soil investigation, the on-site won material was described as clayey slightly silty sandy Gravel and classified as Class 6F1 -Fine grading Selected Granular Fill- according to the Specification for Highway Works MCHW Series 600. The initial parameters of the fill material used for the design were: characteristic friction angle of 35deg, unit weight of 18 kN/m3 and a cohesion of zero.

However, according to the test results of the actual on-site material, the fill was described as dark brown very clayey sandy Gravel and slightly gravelly Clay and classified as Class 2C –Stoney Cohesive Fill-, with lower friction angle and bigger fines content. The parameters of the reinforced soil used for the design where: characteristic friction angle of 28deg, unit weight of 18 kN/m3 and cohesion of zero. This material would be very susceptible to weather conditions and it would require more control and monitoring during its installation and compaction, so a more detailed and thorough testing regime was required to be undertaken in each layer with minimum requirements of compaction, moisture content and CBR values.

2.4 *Testing regime: Cohesive on-site won material*

The testing regime followed during the construction of the RSW using the on-site won material comprises the soil tests according to BS1377: Part 9:1990:

- Plate Bearing test: minimum four (4) tests per layer. Test to obtain the CBR.
- Hand Vane Shear test: minimum three (3) tests per layer.
- Core Cutter test: minimum three (3) tests per layer. Measure of Bulk density and Dry density to obtain the relative compaction. Test also used to control the moisture content.
- Sand replacement density test: minimum two (2) tests even a 3 days. Test mainly use to compare results of relative compaction and moisture content in laboratory.

The minimum requirements for each layer were specified with the following values:

- Minimum CBR: 15%
- Relative Compaction: minimum 95% of maximum dry density (maximum 5% air voids at a dry density equal to 95% of the maximum dry density from 4.5kg hammer compaction test)
- Maximum moisture content: 12%

The Plate Bearing test, Hand Shear Vane and Core cutter were acting as an indicator for the site won performance on a daily basis.

If the test results were below the minimum requirements, the layer needed to be removed completely and replaced with on-site won material from a different batch and retested.

3 REINFORCED SOIL WALL: FINAL SOLUTION

3.1 *Design Soil parameters*

The design for the internal and external stability of the RSW was in accordance with BS8006:2010 and the global stability was in accordance with Eurocode 7 (BS EN 1997-1) design approach 1 and 2. The final proposal consisted of a Reinforced Soil Wall with uniaxial Stratagrids of 120kN/m and 60kN/m as primary reinforcement and compacted on-site won material described as dark brown very clayey sandy Gravel and slightly gravelly Clay Class 2C. The total running length of the RSW was 160m, heights between 2.00m and 13.30m and slope angle of 85 degrees. The final layout of the layers of geogrid and compacted fill material was based on the results of the maximum height section of 13.3m (see Figure 6. Cross Section max. Height = 13.27m)

3.1.1 *Soil Parameters*

In order to perform the calculations we used the following parameters.

- **Reinforced fill:** On-site won material: dark brown very clayey sandy Gravel and slightly gravelly Clay Class 2C (Stoney Cohesive Fill).
  - Friction angle ϕ' = 28deg, Unit weight γ = 18kN/m3, Cohesion C' = 0 kPa (value used for calculations)
- **Retained soil:** very clayey sandy Gravel and slightly gravelly Clay Class 2C
  - Friction angle ϕ' = 28deg, Unit weight γ = 18kN/m3, Cohesion C' = 0 kPa (value used for calculations)
- **Starter layer:** Granular material Subbase Type 1.
  - Friction angle ϕ' = 32deg, Unit weight γ = 18kN/m3, Cohesion C' = 0 kPa
- **Foundation soil:** Firm becoming stiff slightly silty slightly gravelly CLAY.
  - Friction angle ϕ' = 20deg, Unit weight γ = 18kN/m3, Cohesion C' = 90 kPa
- **Groundwater**

  Not taken it into account for calculations. Use of drainage geocomposite Duodrain at the back of the RSW connected to a drainage trench at the base.

3.2 *Reinforced Soil Wall Solution*

The final solution of the RSW based on the design of the maximum height is shown in Figure 6 with the following results:

Reinforced Soil Wall:

- Maximum height : 13.27m
- Slope angle: 85deg
- Base: 10 m (min length for geogrids)
- Embedment: 1.20m minimum
- Starter layer: 300mm Subbase Type 1 with Tenax Biaxial Geogrid for reinforcement and Geotextile for separation
- **Primary Reinforcement:**
  - 43 layers of primary reinforcement with uniaxial Stratagrid SG of 120kN/m (30 layers) and geogrid of 60 kN/m (13 layers)
  - Spacing between geogrids: 300mm

    - Length of geogrids: minimum 10m + wrap-around on the face
- **Fill material:** compacted on site won material class 2C – Very clayey sandy Gravel and slightly gravelly Clay – Friction angle 28deg, Unit weight 18 kN/m3, Cohesion value = 0 for calculation purposes.
- **Facing:** (see Figure 5. Face details)
    - Each two layers (600mm) covered with Landlok TRM (wrap-around on the face) to protect the face from erosion and to avoid any wash-out of the fill material on the face.
    - Formwork: steel mesh B1131 (0.7m x 0.7m) to cover a vertical space of 600mm and to achieve a slope angle of 85deg.
- **Secondary Reinforcement:**
    - 1 layer Tenax biaxial geogrid for the starter layer
    - 3 layers Tenax biaxial geogrid on the top of RSW, for the reinforcement of the piling mat

Reinforced Piling mat: On top of the RSW between layers of Stratagrid 41, 42 and 43 a reinforced piling mat was constructed with 3 layers of biaxial Tenax Geogrid to distribute the loadings of the heavy traffic. For the working platform, imported granular material was used, with a total thickness of 970mm (See Figure.7)

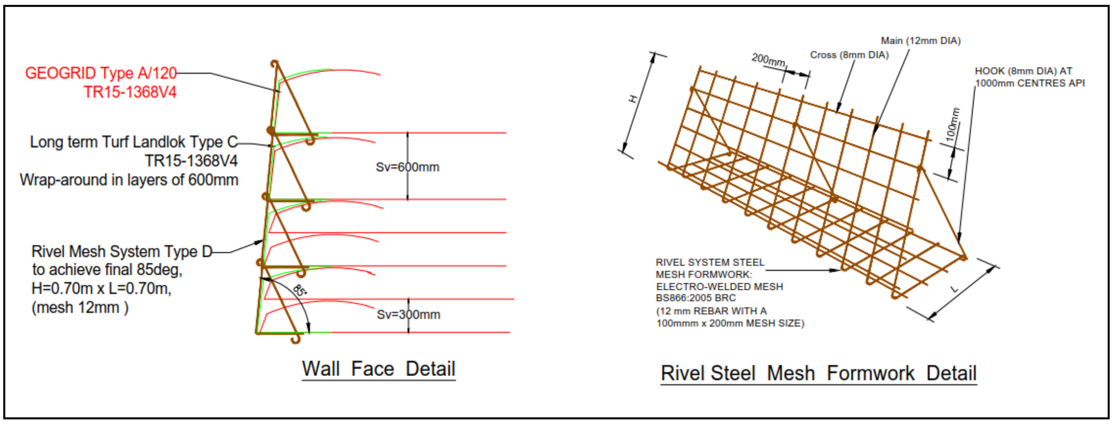

Figure 5. Face detail

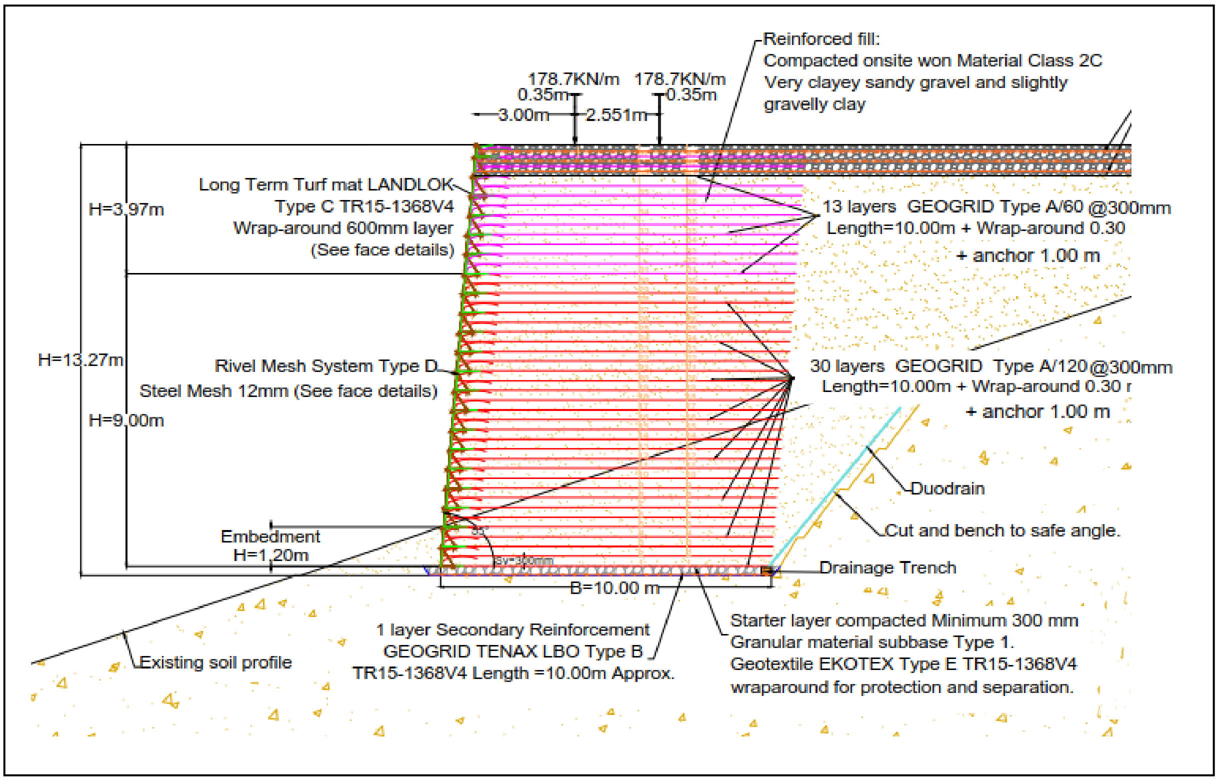

Figure 6. Cross-Section Reinforced Soil Wall Max H = 13.3m

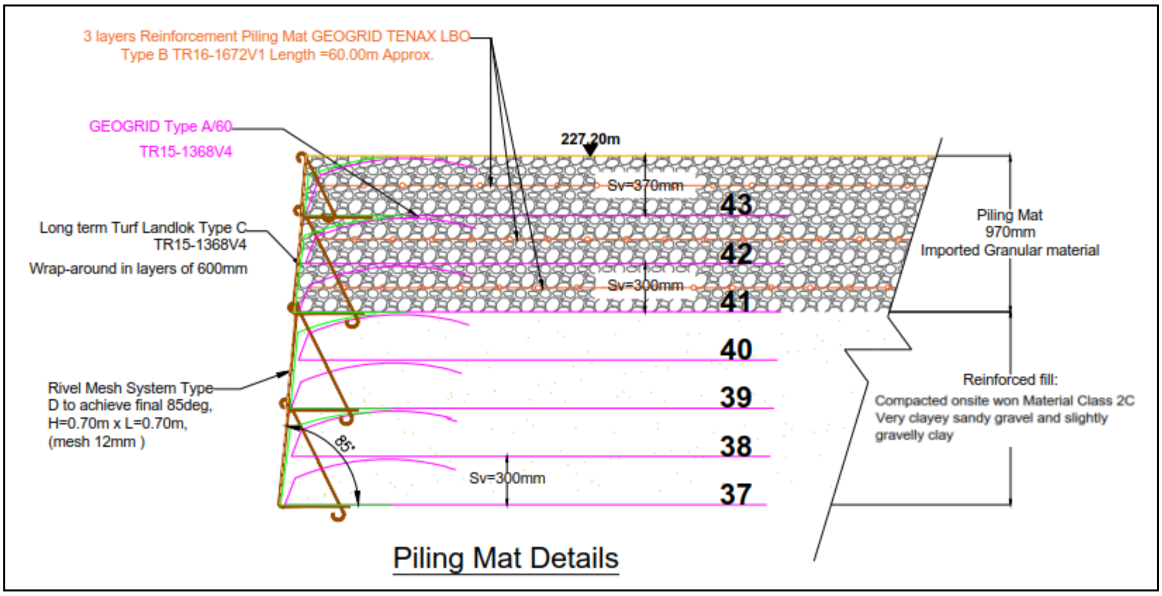

Figure 7. Reinforced Piling mat on top of Reinforced Soil Wall

3.3 *Testing regime results during construction*

During the construction, the testing regime previously described in chapter 2.4 was followed for each layer of the Reinforced Soil Wall.

The first layer given results below the requirements was layer number 4. In this layer the CBR value was 10%, with a relative compaction of 85% and moisture content of 18%. The results were below the minimum requirements, but not so far from the target values (CBR 15% and relative compaction 95%). The layer was left exposed for 2 days, during a period of good weather, and then the layer was re-tested adding some additional passages for the compaction of the exposed soil. The new test results achieved the CBR target of 15%, relative compaction of 95% and the moisture content went down to 12%. The same procedure was followed for layers with CBR results between 10% and 15%, relative compaction between 80% and 90% and moisture content up to 18%, when the weather was dry and sunny. This procedure allowed the subcontractor to work in other sections of the RSW, reducing the delays in the construction programme.

A different procedure was used when there was continuous (and torrential) rain for more than 3 or 4 days and when the tests results were much lower than the minimum requirements: CBR values less than 10%, moisture content above 25% and relative compaction less than 70%. The procedure followed in these cases was:

- Excavate the first two meters from the face of the RSW down to 300mm and replace the on-site won material with a lean mix concrete.
- Replace all the rest of the layer with crush and run material (Granular material Class 6F1).
- Next layer of 300mm to be installed with on-site won material, with layers compacted each 150mm. Additional, to place a drainage geocomposite in strips of 2m, in two meters spacing, between the 150mm layers.

The above procedure was used for layers 10, 11 and 12, where the first tests results were very low and the works stopped due to the bad weather conditions.

The Reinforced Soil Wall was successfully completed with a total of 43 layers, all layers tested according to the testing regime described in Chapter 2.4 and following the additional procedures described above. In average the obtained CBR values were between 18% and 20%, with a relative compaction of 97 to 98% and a moisture content between 10% and 13%. The top three layers (41, 42 and 43) were part of the working platform and were constructed with imported granular material. The CBR values of the top layers were given values between 30% and 35%.

Figure 8. RSW Construction process and breaking through TBM – Elan Valley Bleddfa

4 CONCLUSIONS

The most cost-effective and environmental solution for the required levelled working platform was a Reinforced Soil Wall with on-site won material and geogrids for reinforcement. The final solution consisted on a RSW with a maximum height of 13.3m, slope angle of 85deg and 43 layers of 60 and 120 kN/m geogrids spaced 300mm. The uniaxial geogrids allowed the use of on-site won material as part of the cut-and-fill balance exercise, a key aspect of the project. The fill material was a combination of very clayey sandy GRAVEL and slightly gravelly CLAY, classified as Stoney Cohesive Fill Class 2C. The material was very susceptible to weather conditions and it was required to follow a strict testing regime during the installation and compaction of each layer to ensure the stability and good performance of the structure. On top of the RSW, an integrated granular working platform of 970mm thick was constructed using biaxial Tenax geogrids to distribute the heavy loadings.

The construction of the Reinforced Soil Wall started in April 2016 and finished in July 2016. In total 240 metre access road off the A488 was completed, where 160m was with the Reinforced Soil Wall, reaching a maximum height elevation of 13.3m. A volume of 28,000 m3 approx. of soil was moved as part of the cut-and-fill design providing the level working area required for the construction of the new tunnel of 1.8km to replace the section of the existing aqueduct in Elan Valley Bleddfa.

In December 2016, the tunnel boring machine (TBM) arrived at the end section of the tunnel at Bleddfa, after 5 months of work to complete 1.8 km of tunnel. The 1000 ton mobile crane and the heavy loadings were used to extract the TBM from the reception shaft and the platform on top of the RSW performed well, as expected.

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