Holmestrand, Norway: the world's first high-speed rail station under rock

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A new 14 km double-track high-speed railway through the city of Holmestrand in Norway has greatly improved rail services on the Vestfold line since it opened in 2016. The city's new high-speed railway station is the first in the world to be built under rock. It is accessible by way of several access tunnels from a surface carpark and a public transport interchange. The station was designed to allow high-speed trains to pass at 250 km/h while passengers are standing on the platforms. This required careful management of aerodynamic forces and governed many aspects of design and construction. Special emphasis was also placed on safety, escape routes, ventilation and noise reduction.

1. Introduction

The new high-speed railway station in Holmestrand, Norway, which opened in November 2016, is the world's first to be built under rock. The station is part of a NOK 6.6 billion (£600 million) project to upgrade a 14.2 km section of the 138 km Vestfold line, which runs between Drammen and Eidanger along Norway's south-east coast.

With limited space at the foot of the basalt cliffs adjacent to Holmestrand fjord, the new section of double-track railway between Holm and Nykirke runs mostly in tunnel. The underground station is accessible from the mountain plateau 50 m above by way of lifts and from Holmestrand city centre by way of a 100 m long

pedestrian tunnel (Figure 1). The 1000 t steel acoustic ceiling over the station platforms is designed to withstand aerodynamic forces produced by 250 km/h trains.

The Norwegian national rail administration Jernbaneverket appointed Rambøll as engineering design consultant for the station and 7 km of approach track. The interdisciplinary design required a high degree of coordination, with experts from four countries involved with planning, design and tender documentation. Particular attention had to be paid to ventilation, wind speed and noise reduction inside the station.

The contractor was state-owned rail infrastructure company Bane Nor SF.

2. Geology

The station is located inside a rock cliff with a maximum height of approximately 80 m (Figure 2). The span of the platform hall is 34.5 m and the height is 16 m, with a rock overburden of 40–50 m. Four side halls housing elevators and stairs project about 7 m either side of the main hall.

The bedrock consists of volcanic rocks of Permian age. The thickness of the various lava flows varies from 5 m to 15 m. The main body of a lava flow consists of basalt, and the tops of the lava flows include fragments of solidified lava that have been torn off by lava that was still liquid. Between the different flows, time breaks are visible as disintegration of the rock mass. This is especially evident in the top of the layers, which also includes foreign materials added by water and air transportation. The lava flows can be divided into two main rock type categories: basalt and lava breccias and sediments.

Figure 1. Aerial view looking west of existing and proposed station site (NGI, Vidar Kveldsvik)

Figure 2. Cross-section of station hall and entrance tunnel within mountain (Gottlieb Paludan Architects)

Laboratory tests on samples from core drilling show that the compressive strength varies from 35 MPa (weakest lava breccias and sediments) to 197 MPa (strongest basalt). The Young's modulus varies from 15 GPa to 79 GPa and tensile strength varies from 4 MPa to 12 MPa.

Four fracture sets were identified from core logging: three subvertical fracture sets and one fracture set with an average dip of 17° . Geological mapping during excavation showed that fewer than four fracture sets exist locally. Calculation of the friction angle using the Barton–Bandis shear strength criterion was performed and for numerical modelling and rock support design a friction angle of 44° was used, based on expected normal stresses of 3.5 MPa.

Rock stresses were measured during the site investigations at several locations with three-dimensional over-coring and hydraulic fracturing. Only gravitational stresses exist south of a major fault and in the fault itself, just south of the station hall. Locked-in (remnant) stresses exist north of the major fault – that is, in the station hall area. The vertical stress corresponds to the weight of the overburden. The smallest horizontal stress is parallel to the tunnel axis and is not less than 1.7 MPa, while the largest horizontal stress is perpendicular to the tunnel axis and is in the range of 3–10 MPa. The stress conditions may be described as favourable, and 3.5 MPa horizontal stress across the tunnel axis was used in numerical models and for rock support design.

The typical Q-value for the rock mass hosting the station hall was estimated at 13 ('good' rock mass quality) during the design phase. The geological strength index value was estimated at 67. The

rock support design was based on numerical modelling. The basic (minimum) rock support was specified as 200mm of steel-fibre reinforced sprayed concrete and fully grouted rock bolts spaced 2.2m apart, with bolts 6, 8 and 12m long. At intersections between the station hall and side caverns, rock support was supplemented with an additional layer of sprayed concrete reinforced with lattice girders.

3. Aerodynamics and pressure waves

The new high-speed section runs through a 12.3km long single-tube rock tunnel with a 250m long railway station midway (Figure 3). The station is in an open rock cavern with four railway tracks. Two tracks run along the platforms to provide train access for passengers, while two tracks for passing trains run through the centre of the cavern.

The bidirectional, double-tracked railway tunnel allows running speeds of up to 250km/h. Freight trains are expected to run at a maximum speed of up to 130km/h. The passengers enter the station on foot through the two 100m long access tunnels.

The aerodynamic forces produced when a train enters and passes through the tunnel at high speed are diverse and complicated. Drag and pressure loads are strongly dependent on the pressure waves in the tunnel. Aerodynamic drag in a tunnel increases significantly compared to what is the case in open air. When a high-speed train enters a tunnel, a compression wave is formed ahead of the train that propagates along the tunnel at sonic speed and encounters any

Figure 3. Longitudinal section showing tunnel, transition and station zones

change in the tunnel cross-section. When these pressure waves reach the tunnel exit, the compression wave is partly reflected back into the tunnel, forming an expansion wave, and is partly emitted outside as a micro pressure wave.

A complex wave interaction occurs inside the tunnel due to successive reflections of the pressure waves at the exit and the entry to the tunnel, as well as other trains and cross-sectional changes in the tunnel (Figure 4). A train meets the waves several times during its passage through the tunnel. When combined, the waves can cause aerodynamic loads on the vehicle and tunnel structure. They can also affect passenger comfort if train airtightness is insufficient to attenuate transmission into the vehicles.

Based on the expected traffic pattern at Holmestrand, cyclic loads will occur 4 million times during the station's 100 year design lifetime. Maximum pressure variations in the tunnel and station hall were calculated as 4.1 kPa and 1.5 kPa, respectively. These will occur when a high-speed train travelling at 250 km/h meets a freight train travelling on the opposing track at 130 km/h. Passengers waiting on platforms are directly exposed to these pressure waves, which may produce discomfort such as earache, and give rise to further complications with regard to door operations and escape routes for passengers.

A significant effort was made in the design to determine and mitigate pressure waves. A detailed numerical analysis of trains meeting at various positions (approximately 600 in total) was undertaken to derive the loads to doors and structures, as well as comfort criteria for passengers waiting on platforms. Significant mitigation of the pressure waves was derived from the geometry of portals and smooth connection between the tunnel and station cavern. Major improvements were achieved by the introduction of a pressure-relief tunnel, in which pressure amplitudes have been significantly reduced. The air-friction effect of ballast tracks and the positive effects from irregular tunnel geometry caused by escape tunnels, and other single-point obstacles such as overhead line equipment support masts, help to mitigate the pressure load.

4. Acoustics

In the design process of the new station hall, great effort was made to agree on acceptance criteria for noise. The goal was that

Figure 4. Simplified diagram of pressure waves created in the tunnel and station by a single train

people on the platform should not experience potentially harmful sound pressure levels or unacceptable discomfort. A literature study showed that different acoustic parameters needed to be investigated in order to meet the public's expectations. The design consultant recommended that the following set of criteria should be met

- A-weighted maximum level, LA, F, max <95 dBA
- maximum level infrasound, L, F, max 1–20 Hz <125 dB
- C-weighted peak level, L, C, peak <130 dB.

The values should apply to all train types, speeds and situations.

Due to the development of train types and technology, there is uncertainty related to noise levels from future train types. It was, however, decided that measurements from the airport express train used between Oslo and Oslo airport were to be used. Measurements were taken inside tunnels and outdoors to obtain reliable data for use in further calculations.

The measurement data were used in an acoustic calculation programme to make it possible to calculate noise levels and reverberation time on the platform. The model provided an opportunity to look at different absorbers and noise barriers to ensure an optimal design. The calculations showed that noise criteria would be exceeded if the station hall was too reverberant, and that absorbing barriers were needed to be able to keep the noise levels acceptable.

As a result a decision was taken to use acoustic panels in the whole platform ceiling and into the tunnel on each side (Figure 5). There are also local acoustic panels over each of the platforms, making the expected reverberation time for this large space just above 1 s.

There was also a perceived need for nearby sound-absorbing noise barriers, 2 m high, close to the rail. The maximum level on the platform was calculated to be approximately 100 dBA, and criteria for the C-weighted peak level and infrasound were also expected to be met. As the sound was expected to be a little bit higher than the acceptance criteria, the project team decided to make sure that the noise barrier could be raised to 3.5 m if needed in the future.

After finalisation and before opening, measurements were made of both reverberation time and levels at the platform from passenger trains and trains carrying goods. The measurement showed very satisfying results. Reverberation time was 1 s as predicted, and the maximum level at the platform was between 90 and 100 dB,

Figure 5. Cross-section of station hall showing position of acoustic ceilings and barriers, which limit noise to 100 dB (overhead line equipment omitted for clarity)

depending on the speed and type of train. The lowest levels came from the trains carrying passengers. Both infrasound and C-weighted peak values were way below the acceptance criteria.

Looking at new train types coming in with lower noise levels, the levels are expected to drop even further and the criteria will accordingly be met.

5. Construction

The twin-track railway tunnel, four-track station hall and station entrance tunnels were all excavated using traditional methods such as drilling and blasting. Due to the large cross-section in the station hall, drilling and blasting works had to be divided into several parts. The upper part of the cross-section was divided into sections and excavated in its entirety before the lower part was blasted and excavated. The rock mass was injected in advance before the blasting works to prevent changes in ground water level in surrounding areas.

The station hall acoustic ceiling was then suspended from 686 hangers, each connected to 25 mm diameter rock anchors installed 6 m into the rock above. Each anchor was tested to 2.0 kN and then set to a prestress of 185 kN and grouted (Figure 6). The prestressing was necessary due to the large fatigue loads on the ceiling structure. This was especially important given that the Norwegian national annex to EN 1993-1-9 (SN, 2010) defines the partial factor for fatigue strength (γ_{mf}) as 2.0, compared to the standard value of 1.35 (safe life/high consequence).

There were very small tolerances for the position and inclination of the anchor baseplates as any deviations could cause large deviations at the lower end of the hangers. Deviations could cause extra loads on the connection to the rock that could potentially be of an unacceptable magnitude. Each anchor bolt and baseplate was therefore carefully checked before prestressing and grouting.

Most hangers have an adjustable length up to 3.5 m but some of the shorter ones are fixed. Strain gauges were connected to the hangers to help monitor and control their movement. The hangers were then clamped to HEA360 steel ceiling beams, after which the acoustic panels were mounted to the underside (Figure 7).

Galvanised steel purlins and trapezoidal corrugated steel sheets were then fixed to the upper side of the ceiling structure to protect it from water dripping from the rock above (Figure 8). For maintenance purposes, a walking ladder system is located on top of the ceiling, permitting people to walk, control and check the ceiling parts of the construction which are not visible from the station side. However, the design life of the ceiling is specified to be 100 years without significant maintenance to the primary structures.

In total the ceilings in the station consist of

- over 1000 t of steel
- 3 km of main steel beams
- 686 steel hangers
- 7363 cladding plates over tracks
- 970 cladding plates over the platform
- 11 400 m² of cladding plates in total
- 33 000 screws for the plates
- 150 000 screws and bolts in total.

Figure 9 shows a view of the completed station hall with all acoustic features in place.

Figure 6. A total of 686 steel hangers were bolted to the bare rock soffits of the station hall and tunnel

Figure 7. Station hall ceiling structure under construction (Anne Mette Storvik, Bane Nor)

Figure 8. The ceiling is waterproofed with corrugated steel plates and provides maintenance access

Figure 9. Completed station hall showing acoustic ceiling above tracks, acoustic panels above platforms and noise barriers adjacent to high-speed tracks

6. Fire, evacuation and safety

Fire safety is considered a challenge in underground spaces due to long walking distances to escape, and there are difficulties related to controlling smoke and maintaining visibility for escaping passengers and rescue teams.

The combination of underground public areas with high-speed trains generating high-pressure waves creates conflicts of interest between the public's comfort on the one hand, and overall safety in the case of a fire incident on the other. To control the air flow velocity at platforms and through the access tunnels, measures have been taken to improve the safety for passengers, including the construction of

- a 70 m² cross-section pressure-relief tunnel close to the platform area
- a shielding wall separating the platform from the midway section high-speed tracks
- 'airlock' gates at the entrances of the access tunnels.

The airlocks are essential to avoid unacceptable airflow velocity conditions, and they will prevent possible injuries from happening while passengers pass through the pressure barriers

between the tunnel enclosure and the open space outside. The airlocks at the entrance gates have two access points: one through the sliding doors in series, where at least one is always in the closed position, and the other through a series of two revolving doors. Each revolving door is an airlock device in itself (Figure 10).

To reduce the risk of creating sub-pressure zones in the public area, all doors are open between the pressure zone and

Figure 10. Pairs of sliding and rotating doors at station entrances create 'airlocks' to limit air speeds caused by trains

the airlocks. In addition, pressure-relief dampers were installed where appropriate to reduce pressure differences within the station space. During normal operating conditions, there are no available doors for the public except the airlocks located by the station entrances, comfort rooms excepted.

The design fire loads are based on expected fire scenarios in the relevant trains. The selected scenarios are 30MW for passenger trains and 150MW for freight trains. In case of a fire incident in the tunnel or the station hall (train fire, platform fire or other fire), it is not considered safe to close the fire doors between the platforms and the escape routes for the access tunnels before the trains have reduced their speed significantly. The lack of permanently available safe escape routes from the platforms is a challenge in terms of the public space safety regulations.

There is still no holistic safety code or global standard for safety for underground railway stations. There are a number of national and regional standards related to safety, such as NFPA 130, which deal with relevant fire safety issues. The combination of a high level of fire safety and random pressure fluctuations is not really covered anywhere.

The national fire code states that public areas should be in conformity with the national rules on fire safety, and must therefore comply with the TSI specifications (ERA, 2018). The tunnel and escape routes outside the public area comply with TSI specifications. The underlying safety design principles for the railway stations and their associated premises are performance-based safety designs, which are widely accepted by the national fire code. The principle for design of the infrastructure is to provide the best safety protection to passengers and operational staff as well as to emergency personnel during normal operation and in the event of a fire.

To ensure that the suspended steel structure with attached acoustic ceiling would remain intact in case of a fire in the station hall, the acoustic panels were tested and controlled relative to an ISO 834 fire (ISO, 2014), with a positive result. The purpose was to confirm that the ceiling would remain hanging after 60 minutes, to ensure sufficient time for evacuation.

A key to safety is the railway operation centre, which is alerted of any risks to reduce the likelihood of any fires occurring, to mitigate the consequences should a fire break out by assisting rescue teams and to be prepared for rapid recovery actions of essential rail services after any incident. Once any incident is detected, trains will be slowed to establish low-pressure conditions in the tunnel, allowing the fire-separating doors protecting the escape routes to be closed. All safety systems are manually activated by one action from the operation centre.

All non-public areas are separated from the platform public areas by physical fire and pressure-rated doors. Service personnel undergo clearance to gain access to areas beyond the public areas. Sufficient directional signs and exit signs are provided to ensure that all exit routes, from any floor within the station, are clearly indicated by the configuration of escape routes serving the station (Figure 11).

The surfaces of the underground structures are covered in non-combustible materials throughout. Fire resistance is taken from fire codes or from design fires according to which sets the strictest requirement. A smoke-control system is installed both in the access tunnels and in the train tunnel. In case of an incident, escape routes are equipped with smoke barriers and sufficient

fresh air ventilation, allowing fresh air into the access tunnels to prevent smoke from getting into the escape routes. The train tunnel is equipped with a longitudinal tunnel ventilation system and directional control of smoke to provide a smoke-free path for the evacuation of passengers. The ventilation direction is always from the platform area towards the incident.

To improve safety for train passengers, the platform area is a combined rescue station and safe area. It is designated to be a preferred train stopping point located inside the tunnel system from which escape is easy and fire-fighting means are easily available.

Railway tracks in the platform area are all protected with a water-mist system to mitigate and control fires. This system is designed to prevent damage to structures and ensure a minimal risk of structural collapse. Sufficient water is available throughout the tunnel from the municipal system combined with a separate buffer tank and pressure increase system at the station. The water-mist system is automatically activated by heat sensors. The tunnel fire ventilation system matches the fire-suppression system, and is designed according to a holistic strategy for smoke control, fire fighting and evacuation.

7. Conclusions

The new Holmestrand railway station project is considered unique, both nationally and internationally. The fact that high-speed trains with a speed up to 250 km/h can pass through the station while passengers are waiting on the platform is unprecedented.

The planning process initially started in 2010 and the station was opened for passengers in November 2016 (Figure 12). During a period of nearly 7 years of planning and construction the project team has resolved several issues that would benefit future similar projects.

The project shows the importance of solving issues for several disciplines. To confirm that building a station like Holmestrand could be feasible, numerous multidisciplinary issues had to be solved and clarified.

The geological conditions determined the excavation method and geometrical design of the station. The calculated cyclic loads

Figure 11. Green exit signs are provided throughout the pedestrian access tunnel and elsewhere

Figure 12. The station opened to passengers in November 2016

and temperatures governed construction methods in the station, and the calculated noise level led to the use of acoustic panels in the station.

Combined with a project-specific analysis of fire and evacuation strategy, which itself set further requirements for materials, lifts and water supply, the multidisciplinary tasks were highly influenced by each other.

Due to the lack of equivalent issues, several aspects had to be tested specifically to confirm that they would fulfil the

requirements – including bolts, welds, friction connections and acoustic panels.

One year after the station opened the feedback from the client and the passengers is very positive. In a bigger and more societal perspective, the urban benefits of moving the existing railway away from the city are hard to predict yet are considered positive for further development in Holmestrand (Figure 13).

Figure 13. The new station entrance on the site of the former surface rail tracks

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