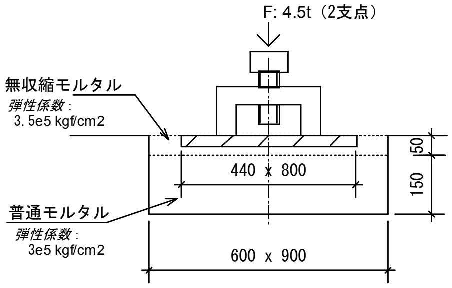

Figure 6: On of the three baseplates of the girders. The steel plates were adjusted to same level and mortar is filled under them.

The reason of girder band before alignment is no clear. Elastic deformation of the steel support and the mortar was about 0.02mm with the conditions shown in the figure, small enough comparing to the amount of the girder bend. It is considered that after the girders and magnets setting on the baseplate, the dry up of the mortar was still in progress, and the middle leg of the girder shrunk more because of larger load. While, it needs further information to make sure of it.

LONG-TERM VARIATION OF THE TUNNEL GROUND

After magnet alignment, the deformation of the girder correlates closely to the deformation of tunnel floor.

The magnets installation was completed in March 1996. From thence we had 14 times of surveys in vertical, and 12 times in horizontal. The levels of magnet are measured with the Wild N3. Standard error is less than ±0.2mm. And, the horizontal is measured with the laser tracker and the theodolite T3000. Standard error is about ±0.5mm.

Figure 7 shows the displacement of magnets in level measured from 1996 to 2012.

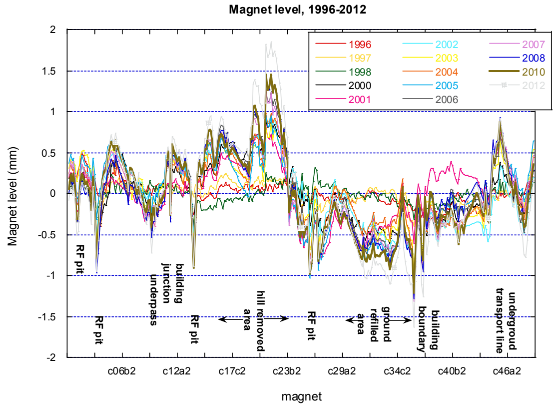

Figure 7: Displacements of magnets in level measured from 1996 to 2012.

To compare the variations between individual surveys and get rid of the measurement error, we processed the data by subtracting a weighted moving average as following [2].

$$\overline{X_i} = \frac{\sum_{k=-m}^{m} w_{i+k} * x_{i+k}}{\sum_{k=-m}^{m} w_{i+k}}$$

And, we take the weight as:

$$w_{i+k} = m + 1 - |k|$$

where, i: current point; m: 2m is averaging length, total number around current point

In the study of the ground motion, the law of ATL is adopted by many researchers. It claims that the relative displacement of two separated points grows with time [3].

$$< \sigma^2 >= ATL$$

We here calculate variance function between surveys:

$$V(\tau)=E((x(t+\tau)-x(t))^2)=\frac{1}{N}\sum_{1}^{N}[x(t+\tau)-x(t)]^2$$

v: variance of a point from its initial position,

τ: time interval in year

And, examine the dependence of RMS displacement ($=\sqrt{V}$) on time interval τ.

Figure 8 is the correlation of the RMS displacement and time interval, averaged for all measurement points.

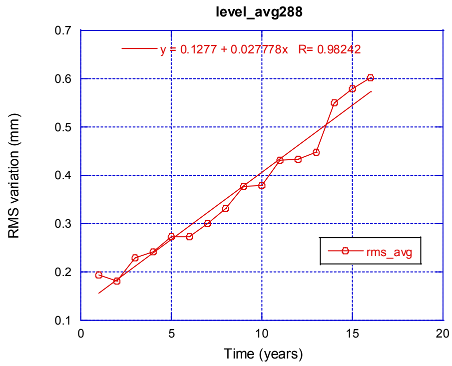

Figure 8: Correlation of the RMS displacement and time interval, averaged for all measurement points.

It is estimated that in the vertical, the average RMS displacement varies at a rate of

$$\sigma = 0.028\ T\ \text{(mm)}$$

where, T: time interval in year.

RMS displacement varies from 0.2mm to 0.6mm in sixteen years. For the more, the variation is seen no sign to slow down.

For each point the ground deterioration rate can be calculated. Figure 9 gives the locations that had large movement. At some places of the ring the deterioration are around 0.06mm/year, almost located at the RF pits, tunnel junctions and SSBT etc. where have underground structures. The girders that had large deformations ride just on the places above.

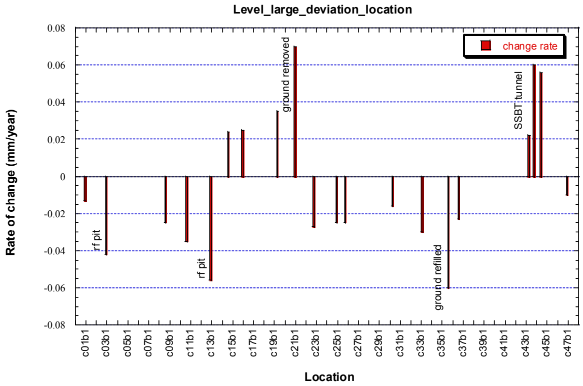

Figure 9: Locations that had large ground movements, some are around 0.06mm/year.

RECONFIRMATION OF THE GIRDER DESIGN.

The girders should have had little deformation because the design criterions was 0.02mm for the sag. While, actual bend are 10 times of this value in some girders. Girder design is reconfirmed with the ANSYS. With three legs and load conditions shown in figure 11, it is confirmed that sags for three types of girder are under 0.01mm.

However, it was on assumption of the ground is rigid. Ground movement makes the situation different. Let's see figure 5 once more:

- Both the magnets and the girder of C37B were bent down in the middle for ~0.3mm.
- C02A and C36B bent up in the middle for about 0.15mm.

The shapes of the girders surfaces are plotted in figure 10, when taking count of the levels of tunnel floor.

What had occurred is the one of the three legs of the girder are ride on the ground where had sunk a lot in past years.

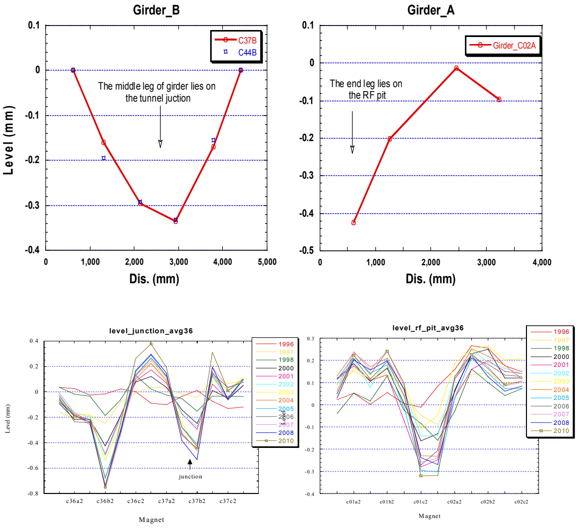

Figure 10: Shapes of the girders surfaces (upper) and tunnel floor levels (lower) of the girder C37B and C02A.

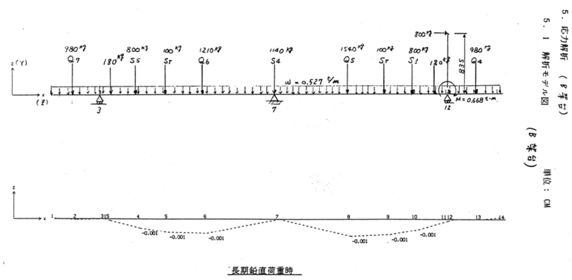

Figure 11: Deformation calculation of the girder with 3 legs. Maximum sag is 0.01mm, for three types of girders.

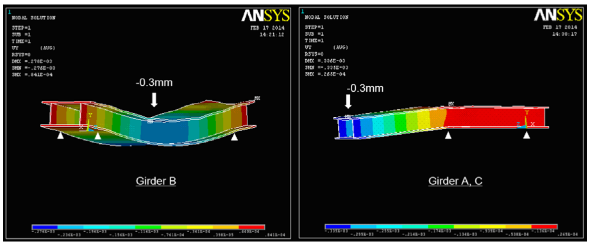

Figure 12: Maximum deformations reach 0.3mm on assumption of the ground settlement large than 0.3mm.

Because of the floor settlement, the supports of 6-point could become 4-point to the extreme and maximum deformation of the girders reaches 0.3mm as shown in figure 12. Actually, the case of C37B mentioned above just verifies the analysis.

CONCLUSION

The magnets on girders were observed have been displaced systematically. To investigate the cause, the shapes of girder surfaces were measured.

It is evident the girders were bent in the middle. Before we aligning magnets on the girders the bend had occurred. It is considered due to the uneven shrunk of mortar of the girder baseplates.

After the alignment of the magnets, deformation of girders was dominated by the movement of tunnel floor. Analysis shows that in average, RMS displacement of the floor varies at a rate of 0.028mm per year in the vertical. And, floor settlement in short range is one of the causes of the girder deformations.

Settlement of the tunnel floor breaks the assumption of girder design that assumes the ground is rigid. So, the girder deformation is larger than expected. In extreme case, the girders could be bent by 0.3mm, if the number of girder supports become 4 due to floor settlement.

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