Ground Motion Expectations for the LCLS Undulator Hall

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November 9, 2004

Abstract

The Undulator Hall (UH) for the LCLS will consist of a tunneled structure completely beneath the “berm” at the east end of the Research Yard. This location should provide better thermal and geologic stability compared with the previous siting at ground level in the Research Yard. Nevertheless, microscopic motion of the tunnel foundation will contribute to misalignments among quadrupoles and reduce the time interval required between beam based alignment sessions. Based on historical measurements of slow ground motion at the SLAC site and measurements of atmospheric pressure effects, assuming a girder support system we estimate that during the first three years of operation the interval between periodic beam-based re-alignments should be about one week. Implications for the support system stability tolerance and the maximum range of motion to be accommodated are also discussed.

1 Introduction

The SASE FEL process upon which the LCLS is based depends on extremely precise synchronism of the undulating motions of the electron beam with the phase of the X Ray radiation produced by the beam as it passes through the undulator magnet. Synchronism requires both very accurate magnetic fields within the undulator as well as an ultra-straight electron beam trajectory. The required trajectory straightness can be obtained through a Beam Based Alignment (BBA) procedure, which should yield a

trajectory that is straight through the undulator to better than 2 microns over 10 meters¹. However, once the beam is tuned up, even microscopic relative motion of quadrupoles will significantly distort the trajectory and cause the path length to increase, thereby breaking the synchronism with the X Ray radiation phase. Beam Position Monitor (BPM) motion, while not directly affecting the electron beam trajectory, in practice may not be distinguishable from real orbit changes and lead to erroneous corrections which have the same net effect as quadrupole motion, especially if such motions occur at the same time as unwanted quadrupole motions. Pointing stability of the X Ray beam is also affected by quadrupole of BPM motion but is amenable to feedback.

Uncontrolled relative motion of the quadrupoles and BPMs will result from distortions of the UH foundation on which the support system rests, as well as distortions in the support structures themselves. Assuming the floor is closely coupled to the surrounding ground, the extreme trajectory sensitivity implies the remarkable consequence that, because of ground motion, the required alignment tolerance will not persist for long. Even the velocity of ground motion typically measured on a geologic time scale, and/or distortions of the ground shape comparable with the curvature of the Earth, can take the quadrupoles and BPMs out of alignment in a matter of days. On the other hand, smooth and predictable operation is fundamental to

¹Simulations show that for the LCLS running at 1.5 Angstroms if the electron beam develops a 2 micron rms deviation from a perfectly straight line over a distance of about 10 meters, the FEL saturation length will increase by one gain length.

the LCLS facility specifications, with a minimum of 90% availability required for an estimated 6000 hours of operation per year. The mechanical stability of the Undulator components and Undulator Hall floor must be good enough to get from one BBA session to another without going out of alignment tolerance. During operation, only a small fraction of the time can be allocated to BBA and this will have to be scheduled — not done on an “as needed” basis.

To address these challenges the LCLS design includes a Position Monitoring System (PMS) consisting of Hydrostatic Level Gages and a Wire Alignment System which will monitor changes in the relative positions of quadrupoles, BPMs and girders. In principle if the PMS worked perfectly, undesirable motions could be corrected either through the remotely controlled CAM based positioning system, or by simply changing the database offsets for the BPMs. It may or may not be possible to make these changes during operation. In any case, the PMS is not expected to work perfectly all the time. For one thing the mechanical link between the quadrupole and BPM centers and the PMS will distort significantly due to small temperature or thermal flux changes as well as due to small incidental mechanical forces. Because of mechanical constraints, this link must be of order 30 cm in length. To hold the shape to a micron or so, for roughly 100 such pieces, during extended periods of operation, is challenging. Electronic offsets in the BPM electronics may also be suspected of shifting. If the PMS readings are drifting we may erroneously try to correct the motions which are not real, or we may ignore real drift because it can’t be distinguish from instrumental effects. Whatever the actual performance of the PMS is, understanding and improving the stability of the Undulator Hall foundation is a common sense approach to mitigating this risk.

In addition to slow ground motions, rapid ground motions consisting of earthquake transients or vibrations from cultural sources have also be extensively analyzed for the SLAC site[1, 2]. These are not as much of a concern for the LCLS performance. A substantial earthquake will require re-alignment but is expected to happen very infrequently. Vibration levels at the site have been measured and are roughly two orders of magnitude less than would sensibly af-

fect the X Ray beam.

A previous technical note on this subject [3] addressed the question of the ground motion of the Undulator Hall based on siting the UH partly in the underground Beam Switchyard and partly in the Research Yard. During the LCLS conventional facilities Title I design, a more favorable site was established which requires tunneling beneath the so-called ‘berm’ starting on the east end of the research yard. This notes addresses the new location and considers more historical data from the SLAC site as well as other laboratories.

2 Historical Data

Historical data on long term ground motion at a number of accelerator facilities has been taken over many years and published. At the SLAC site there are collections of data spanning up to 17 years for the LINAC, 6 years for PEP and several weeks for the FFTB. The Linac and PEP data are particularly relevant to the UH because they are in a similar geologic condition. Other laboratories that have taken and analyzed multiyear motion of the accelerator housing are LEP, HERA and APS. We will cover the SLAC data most thoroughly because of its relevance to the UH site. However, differential settlement rates at all laboratories are similar, with the possible exception of the HERA foundation which is built on sand.

Essentially all the data show that long term ground motion is largely deterministic in the sense that points tend to keep moving at more or less the same rate in the same direction for decades. As a result the rms of elevation measurements tends to grow linearly with time and does not obey the ATL law. This was recognized as a source of error in interpreting vibration data which can lead to an overestimate of the the “A” coefficient[4]. Conversely, ATL estimates based on short term data can lead to underestimates of the slow ground motion.

2.1 SLAC Linac Data

Starting shortly after the construction of the SLAC Linac in 1966, laser alignment data was taken period-

ically to measure the straightness of the 3000 m long support structure that is mounted on the floor of the Linac housing.² This data is unique in that it measures both vertical and horizontal deviations from straight with the same technique. A set of nearly 300 Fresnel gratings spaced 12.3 m apart, one per support girder, extends the length of the Linac and through the Beam Switchyard and can be individually inserted into a laser beam. The deflection of the laser by the gratings (which act as lenses) is measured at a target at the end of the linac and indicates the horizontal and vertical offsets of the gratings center with respect to the (presumed straight) laser beam. Annual and some seasonal data were taken.

A plot of the cumulative 17 year vertical motion is shown in Figure 2. During this period changes in elevation range from -17.5 mm to $+9.4$ mm. The average elevation change is near zero. Observations noted by Fischer include:

- The tunnel sags in regions of fill.
- The tunnel rises in regions where soil was excavated.
- There are no clear cut correlations of motion with any of the “inactive faults”.

Data of horizontal motion (not plotted here) are similar in character to the vertical data but the motions are somewhat smaller.

Of particular interest to the LCLS is the differential settlement between adjacent Fresnel gratings. The 12.3 m separation of the gratings is quite similar to approximately 11 m separation of the support points for the girders that will hold the undulator components and the 10 m field gain length used for tolerance setting. Correlations of ground motions over distances equal to ($\approx 2\times$ the gain length) or less are most important to the FEL performance. In the Linac data correlations over longer separation distances can be calculated directly. Figure 1 shows the increase in rms elevation changes for points 1, 2, 3, and 4 girders apart. The rms value grows with

Figure 1: Correlation of rms elevation difference for targets separated by different distances are plotted from the 17 year cumulative data for the Linac.

increasing distance from 1.43 mm at 12.3 m separation to 3.61 mm at 49 m separation. In Figure 3 is plotted a histogram of the average over 17 years of the rate of elevation differences per day between adjacent Fresnel gratings. The standard deviation is $0.23 \mu\text{m/day}$. The data is not normally distributed. There are substantial tails and a skewness that indicates an excess of large upward motions, even though the average is zero. About 5% of the points are outside of $\pm 0.5 \mu\text{m/day}$.

The 17 year average settlement rate was significantly less than the rate in the first few years of operation. An average time dependency model was worked out by Seryi and Raubenheimer [5] for points on the SLAC Linac tunnel. Based on this fitting, the average rate of settlement over the first three years is about twice the average rate over 17 years. It is also clear that the settlement rate, though decreasing, continues at significant rates past 17 years. The fitting time constant in their model was 30 years.

Seasonal effects, especially due to changes in the water table, were observed and analyzed by Spranza[6]. He found upward displacements in the winter and downward displacements in the summer superimposed on more or less constant settlement velocities. The seasonal effect was fairly close to periodic and correlated with the amount of rainfall. The

²Although plots of this data are easily found in the literature, at this time the actual numerical data resides only on some fan-fold printouts in the SLAC archives.

Figure 2: Cumulative vertical motion of targets along the SLAC Linac from 1966 to 1983.

Figure 3: Histogram of rate of change of differences in elevations between adjacent targets 12 m apart in the Linac, cumulative over the period from 1966 to 1983.

vertical and horizontal motions were of similar magnitude and ranged up to peak-to-peak amplitude of about 1.3 mm. It appears that the spatial correlation evident in Spranza plots of the seasonal effect resembles that of the overall settlement data. The depth of the SLAC Linac tunnel floor is about 35 ft below the finished grade and slopes at 0.5% downward to the east.

2.2 PEP Historical Data

Elevation data for points along the PEP ring were recorded by F. Linker and in a series of *PEP Technical Memos*. The first data was collected in 1979 soon after construction was completed. Data taking continued until 1989. Though both radial and elevation data were taken, elevation measurements from a liquid level measurement system are the most relevant to the UH situation. The measurements were taken at approximately 100 points spread around the ring for an average spacing of 21 m, about twice the spacing of the Fresnel gratings in the Linac.

Figure 4 shows a histogram of data taken from an elevation plot by Linker covering the period between June 1985 and March 1987. The numerical data for the histogram was ‘digitized’ by hand from the plot for the analysis. The rms value is $0.54 \mu\text{m}/\text{day}$ which is not much different from the Linac data for 24 m spacings, averaged over 17 years, which is about $0.37 \mu\text{m}/\text{day}$.

Linker presented a summary of the time dependence of the settlement rate of the PEP floor in a paper in which he estimates what to expect for the rate of settlement in the SLC[7]. The data printed in the paper and some additional data (added by Pitthan?) are plotted in Figure 5. Evidently the maximum settlement rate in the PEP tunnel decrease dramatically during the first year. After two years the rate is only very slowly decreasing and continues to be close to $\sim 2 \mu\text{m}/\text{day}$ even five years after construction.

The Linac was constructed with the “cut and cover” method exclusively, while PEP was constructed with a combination of cut and cover and roughly 30% tunneling. The UH construction will be exclusively tunneling. The two tunneled regions of PEP are approximately from sectors 9:20 to 10:30

Figure 4: Histogram of nearest neighbor velocities for PEP, averaged over a 1.7 year period starting in June 1985.

Figure 5: The maximum rate of change of elevation of points around the ring were measured periodically starting soon after PEP tunnel construction.

and from sectors 3:15 to 4:15. In the first tunneled region the elevation data shows the most stable behavior, while the data from sectors 3:15 to 4:15 is typical of the whole ring.

2.3 FFTB Data

A wire alignment system extending from inside the Beam Switchyard through the FFTB housing in the Research Yard was used to monitor magnet positions as part of the final focus test beam experiments[8]. The wire alignment system measured the combined effects of tunnel and support structure motions. The most salient observation was that there was a strong daily variation in elevation of $\sim 30 \mu\text{m}/\text{day}$ between the Beam Switchyard and the Research Yard. This rapid and large motion contributed to the decision to site the UH completely underground and out of the Research Yard.

2.4 Other Labs

Extensive elevation data was collected covering the years 1993 through 1999 and analyzed at LEP[9, 10]. First beam was in 1989 so rapid motion associated with initial construction should not be present in the data. This data is characterized by average

rms rates of elevations changes between adjacent quadrupoles separated by about 40 m ranging from 0.14 to $0.55 \mu\text{m}/\text{day}$. A histogram of quadrupole-to-quadrupole elevation deviations shows a non-normal distribution similar to that for the SLAC Linac data. Most of the points (80%) are fit to a gaussian with sigma of 0.6 mm. The remaining points lie outside the tails of the core distribution and fit to a gaussian with a sigma of 1.5 mm. These sigma values correspond to 6 year average rms motions of 0.27 and $0.68 \mu\text{m}/\text{day}$, similar to the SLAC linac 17 year average rms rate of $0.23 \mu\text{m}/\text{day}$.

3 Geology Along the Undulator Hall Alignment

Recent boring data was taken at two points along the UH alignment: point “A” near the highest point of the berm corresponding to the upstream portion of the UH, and point “B” roughly in the middle of where the UH will go [12]. The bores were taken to a depth below the proposed tunnel and no ground water was encountered. Point “B” went through 18.5 ft of fill before entering the Ladera sandstone that is common to both bores. The fill was added sometime early in the SLAC site construction.

Figure 6: Elevation view of the Undulator Hall per Title I design.

The topography along the UH is indicated in Figure 6. The fill is located on the right hand side of the hill. The downstream portion of the the UH has relatively light overburden. The Research Yard is immediately to the left of the UH in the figure. Ground water hydrographic maps indicate the water table is highest near the Research Yard and drops off toward the east (to the right in the figure). There are no active faults noted. The possibility of clay pockets, which would tend to swell when wet, is not excluded as such pockets were found in the nearby PEP tunneling.

4 Short Term Motion

The slow settlement effects that are evident in the historical data are generally of the form:

$$y_{rms}^2 \propto T^2 L$$

Superimposed on the slow settlement motions, which take place on the month—year time scale, the floor of the undulator hall will experience motions on an hour—day time scale for which the rms deviations grow in proportion to the square root of time. Eventually the settlement effects will dominate over all other effects because of their linear time dependence. However, the short term effects have a significant amplitude and play a important role in determining the day to day orbit stability.

Short period motions in the SLAC linac were studied extensively by Seryi [11] using 1 Hz position data from the midpoint of the linac. He found that the linac alignment was clearly responding to atmospheric pressure and tidal effects. The pressure response was especially pronounced and had an average vertical displacement of $6 \mu\text{m}/\text{mbar}$. Surprisingly, tidal effects were also clearly observable in the data. It turns out that because of the proximity of the coastline, the tidal effects were $\sim 100\times$ larger than what would be expected far from the coastline.

4.1 Tides

The tidal induced motion is not expected to be significant for the LCLS. The amplitude measured on the linac with a 3000 m baseline was around $10 \mu\text{m}$. Because the origin of the tidal effect is excess weight of water at the shoreline many miles away bending the continental plate, the tidal stresses at the SLAC site are spread over a great depth. Variations in mechanical properties of the ground over the scale of interest for the LCLS will not effect the overall average stresses and strains in the area. Tunnel foundations will simply ride on a very slight curvature change to the earth. With this model in mind, tidal deflection will be proportional to the distance between points squared. Scaling from 3000 m to 10 m for the LCLS therefore gives negligible motion.

4.2 Weather

Foundation motion caused by atmospheric pressure changes is expected to follow the local mechanical properties of the ground. Differences in elevation motion should be, on the average, proportional to the square root of the distance between measurement points. Thus the $6 \mu\text{m}/\text{mbar}$ response measured over a baseline of 3000 m can be scaled to the LCLS field gain length of 10 m to yield an expected differential vertical motion per pressure change of $0.35 \mu\text{m}/\text{mbar}$. In periods of consistent weather, a typical rms pressure variation during one day is around 1 mbar. However, when a new weather system moves in, a pressure change of more than 10 mbar can occur in a period over just a few hours. Such events will cause rapid differential motions of the UH floor of order $5 \mu\text{m}$ and should be observable on the electron beam trajectory.

Atmospheric pressure data taken at SLAC during the period of time the linac midpoint data was collected show that the rms of pressure fluctuations grow roughly with the square root of time, at least for intervals up to two weeks, as can be seen in Figure 7. A fit to the data gives an estimate of the time dependence of the rms pressure fluctuations during the long baseline measurement of $0.84 \text{ mbar} \times \sqrt{\text{days}}$. It turns out to have been a relatively quiet period of time for the weather when the data was taken.

Pressure data from essentially the entire year of 2003 yields an rms pressure deviation over 24 hours of 3.1 mbar, which corresponds to an rms height deviation of points 10 m apart of $0.35 \times 3.1 = 1.1 \mu\text{m}$. As discussed in section 4.3, there is reason to believe the weather effect for the hour-day timescale may be a significant component of the *ATL* motion. Differential motion of $1.1 \mu\text{m} \times \sqrt{\text{days}}$ is equivalent to an *A* of $1.4 \times 10^{-6} \mu\text{m}/(\text{ms})$.

4.3 ATL Motion

In addition to the weather and the tides there remains motion on the hour-day timescale that correlates with the *ATL* law. Seryi and Raubenheimer [5] estimated the value of *A* for the SLAC site from the historical data, which was taken over a long period of time and includes pressure effects. Their estimate of

Figure 7: The average rms pressure change as a function of elapsed time is plotted. The average was taken over several separated periods of time concurrent with the long baseline data taking. A square root of time fit is shown as well. Pressure changes tend to be episodic with dramatic changes occurring over periods of less than one day.

Figure 8: Absolute atmospheric pressure measured in the main drive linac for most of the year 2003.

A is $\approx 5 \times 10^{-7} \mu\text{m}/(\text{ms})$ for the time scale of 1 day. However, in ref [11] Seryi correlates the parameter A with the amplitude of the atmospheric pressure spectrum. Extrapolating to zero pressure amplitude one can conclude that the non-pressure dependent value of A is of the order of $1 \times 10^{-7} \mu\text{m}/(\text{ms})$ or less — much less than what would have been expected from the historical data. These observations are consistent if most of the ATL motion observed on the hour-day time scale in the historical data was due to changing atmospheric conditions, and that such weather was relatively quiet during the period the long base-line measurement were made.

Nevertheless, since the effect of weather, as modeled in this paper, has the same time dependence as the ATL motion, it is only of academic interest whether the cause is weather or some other source. We choose to be conservative and assume the existence of ATL motion, independent of the weather, which corresponds to the longer term average value for A arrived at by Seryi and Raubenheimer of $5 \times 10^{-7} \mu\text{m}/(\text{ms})$, keeping in mind that much of this may in fact be due to the weather. This implies that for points 10 m apart the rms relative ATL motion should evolve as $y_{rms,ATL}[\mu\text{m}] = 0.7\sqrt{\text{days}}$.

5 Predicted Ground Motion for the Undulator Hall

In this section we use the historical and short term data to make a prediction of the rate of differential motion to expect for the Undulator foundation. The estimate should only be regarded as approximate — perhaps within a factor of two the real behavior. In the historical data, almost all slow ground motion could be “explained” by some feature or other that is peculiar to the area is question. Because peculiar features may not be recognized as such until after peculiar behavior has been observed, any prediction of ground motion is likely to be wrong to some degree.

For simplicity we refer to the expected ground motion averaged over the first three years of operation. This is a critical period during which the machine is commissioned and its basic performance is estab-

lished; the motion will be worse at the beginning and better at the end of this period.

We first discuss the slow and fast motions separately and then their combined effect. The discussion is explicitly in terms of the vertical motion. The horizontal motion is expected to be somewhat less than the vertical, but of the same order and have the same time dependence.

5.1 Slow Ground Motion Estimate

The slow ground motion in the first three years of operation is estimated to be twice as much as the 17 year average linac data for 12.3 m separation. That is, we should expect rms velocities for neighboring support points of the Undulator girders to be about $0.5 \mu\text{m}/\text{day}$, with the actual shape of the distribution matching that of the Linac data. A histogram of the expected nearest neighbor elevation velocities due to settlement is plotted in Figure 9. Almost all points in the UH are expected to move at a rate in the range of $\pm 1 \mu\text{m}/\text{day}$. After three years the ground motion rate should be reduced to roughly one-half as much as predicted here. This amount of slowdown is consistent with the PEP data shown in Figure 5 as well as the fit to the Linac data by Seryi and Raubenheimer. Of course, during the first year, the average motion will be higher than the predicted average for the first three years.

5.2 Fast Ground Motion Estimate

The fast ground motion (hour-day) during the first three years is estimated to be the incoherent sum of the ATL and weather effects (tides are not significant). No enhancement factor for fast ground motion for the first three years of operation is included.

5.3 Combined Ground Motion Estimate

Estimates for the fast and slow vertical motions are incoherently combined in Figure 10. The ATL and weather motion dominates during the first four or five days after alignment; thereafter settlement motion takes over. The motion in the figure refers to

Figure 9: Predicted distribution of UH vertical motion due to settlement for points separated 10 m apart, assumed to be averaged over the first three years of operation.

the average rms elevation difference of points 10 m apart. It is assumed the vertical deviation is with respect to a best fit line through the entire undulator and the average is taken over arbitrary starting times. It should be noted that the actual rms motion will exceed this expected value about half of the time and that fluctuations about the average are large. If re-alignment is to be done on a periodic basis the re-alignment interval must be short enough to avoid statistical fluctuations that would taken the alignment out of tolerance.

Various factors were considered in making the estimate: similarity of geology and location, startup effect, tunneling vs cut and cover, and the presence or absence of fill. No benefit was given for tunnel construction of the UH, as compared to the Linac which was cut and cover. The PEP data show a modest benefit for tunneling. On the other hand a good portion of the UH is relatively shallow compared with the Linac and will have a substantial amount of fill over it, albeit 40 year old fill. The PEP experience showed that unexpected clay can be found in the vicinity of the UH. If such clay is present seasonal swelling effects could cause more ground motion than is predicted here.

Figure 10: Predicted vertical differential motion of the points 10 m apart for the foundation of the undulator hall during the first three years of operation.

6 Re-alignment Interval

Re-alignment of the electron beam trajectory will be beneficial if the electron beam trajectory has distorted by more than an rms of $2 \mu\text{m}$ over 10 m from the last time it was tuned up. The amount of time that elapses before the alignment deteriorates to this level depends not only on the motion of the Undulator Hall foundation, but is also dependent on the design and stability of the support system and the strength of the focussing optics. For example, the beam trajectory is less sensitive to motion of weaker quadrupoles because their steering effect is weaker. Similarly, coupling the motion of quadrupoles by putting multiple quadrupoles on a single girder reduces the effective steering strength considerably, making the beam trajectory more tolerant of foundation motion.

The design of the support system of the undulator consists of a girder supported off the floor, holding up three “cradles”, each holding a quadrupole, a BPM, and an undulator segment. The cradles are remotely positioned using a cam based positioning

system. During BBA the cam system will be used to move the cradles so as to position the BPMs, quadrupoles and undulator segments on the desired orbit axis. As the alignment deteriorates, quadrupole positions change and the electron beam trajectory distorts. Re-alignment will be necessary before the resulting cumulative phase error reaches 360 degrees at the end of the undulator.

Deterioration of the quadrupole alignment will be caused by ground motion which moves the girders, as well as by distortions in the support system. For that portion of the alignment deterioration due to ground motion (leaving aside the motion introduced by the support system itself), the minimum interval of time between BBA sessions can be estimated from the expected rate of differential motion of the floor. We assume the girder model discussed in reference [13]. In this model three quadrupoles are mounted on an assumed perfectly stable girder which is kinematically supported at points roughly 11 m apart. Because of the correlation of the motion of the adjacent quadrupoles, their steering effect on the electron beam – xray beam phase error is suppressed by a factor of 5. An overall phase error for the undulator of 360 degrees, which corresponds to approximately one gain length increase in the saturation length, will on the average be reached if the foundation points to randomly move within a ± 20 micron window from their aligned positions. The rms value of this window is $11.5 \mu\text{m}$. According to our estimate given above, it will take approximately 19 days to reach this limit. Therefore, if foundation motion is the only source of motion of the quadrupoles, the frequency for BBA needs to be at least an average of once every 19 days during the first three years of operation. Consistent operation of LCLS would require the BBA interval be set at a short enough time that there is relatively little chance of going out of tolerance and losing performance; once per week might be a natural choice depending on how stable the support system is.

Additional random motion of the quadrupoles due to distortions of the complex support system, if large enough, can significantly decrease the re-alignment interval. Conversely, there is little benefit if the support system stability is very much better than the foundation motion stability. An overall stability tol-

erance of the support system that is a factor of two less than the foundation estimate given here would reasonably accommodate the uncertainties in the estimate. The foundation motion after one week (presumably the re-alignment interval) will on the average be about $5 \mu\text{m}$, so the overall support system tolerance on quadrupole positions should be around $2\text{-}3 \mu\text{m}$.

7 Range of Motion

Another implication of the ground motion, besides required frequency BBA, is that sufficient range of motion must be included in the design of the support system. Based on the Linac data over a twenty year lifetime we can expect that some support points along the undulator will need to be moved at about 20 mm due to ground motion. It would be most convenient if the support of the girders could accommodate this range. Additional range will be needed to accommodate locational and size tolerances, leading to a recommended range of approximately ± 25 mm. Because the recommended range is so large, shimming may be a practical component of the range adjustment scheme.

8 Conclusions

Lessons from previous studies indicate that in designing the UH tunnel we should be careful to obtain good consistent drainage, to keep changing moisture levels from swelling the ground, and to avoid putting fill above the tunnel. Because of the favorable new siting of the UH, during the first three years of operation we should expect to measure differential vertical ground motion due to settlement of points 10 m apart at rates typically within a range of $\pm 1 \mu\text{m}/\text{day}$, and an rms rate of about $0.5 \mu\text{m}/\text{day}$. Horizontal motions will be similar but somewhat smaller. Additional motion primarily due to the weather will have significant effect on alignment over time periods of up to 4 or 5 days. Combining the weather and settlement motions and assuming a girder support scheme, leads to an estimate of the time interval for periodic BBA

of once a week. Stability tolerances for the support system should be held below the expected foundation motion, implying a tolerance of the order of 2-3 μm over 1 week. Finally, sufficient adjustment range, or provision for shimming, should be designed into the support system to accommodate a total motion of up to ± 25 mm during the life of the LCLS.

9 Acknowledgements

The author would like to acknowledge the generous help received from Jo Beth Folger, Rainer Pitthan, Robert Ruland, and especially Andrei Seryi.

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