Agenda Item No. (3)

To: Building and Operating Committee/Committee of the Whole
Meeting of December 16, 2021

From: John R. Eberle, Deputy District Engineer
Ewa Z. Bauer-Furbush, District Engineer
Denis J. Mulligan, General Manager

Subject: **APPROVE ACTIONS RELATIVE TO REDUCING WIND INDUCED SOUND EMANATED BY THE GOLDEN GATE SUSPENSION BRIDGE WEST RAILING**

RECOMMENDATION

The Building and Operating Committee recommends that the Board of Directors approve actions relative to reducing wind induced sound emanated by the Golden Gate Suspension Bridge west railing as follows:

1. Approve an installation of 1/16-inch thick tapered U-shape aluminum clips with 1/16-inch thick vibration damping material inserts on both edges of the pickets of the new western bridge railing for the full length of the main span of the Suspension Bridge as described in this staff report;
2. Approve an addition of a Suspension Bridge Sound Reduction Project in the FY 2021/22 Bridge Division Operating Budget with the estimated cost of $450,000; and,
3. Authorize the filing of a Notice of Exemption under the California Environmental Quality Act (CEQA) for the Suspension Bridge Sound Reduction Project;

with the understanding that sufficient funds are available in the Bridge Division Operating Budget.

This matter will be presented to the Board of Directors at its December 17, 2021, meeting for appropriate action.

SUMMARY

As part of on-going Contract No. 2016-B-01, *Golden Gate Bridge Physical Suicide Deterrent System and Wind Retrofit Projects,* the construction contractor has installed wind retrofit elements on the west side of the Suspension Bridge main span. The wind retrofit consists of a replacement of the original west bridge railing having wide pickets with a new railing having thin pickets and installation of a wind fairing on the outside of the bridge truss at the sidewalk level.

The aerodynamic stability of long-span cable-supported bridges is sensitive to the solidity of their external railings. Solid railings or barriers at the windward side of a bridge deck truss promote the formation of strong rolling air vortices that shed off the bridge side and across the deck truss in the direction of the wind. Ultimately, this type of phenomenon could lead to aerodynamic instability of the deck truss during extreme wind events. A well-known example of a catastrophic aerodynamic instability is flutter, which is a diverging instability (twisting of the deck truss) with increasing wind speed, and was ultimately the cause of the Tacoma Narrows Bridge collapse.

To prevent the formation of air vortices on the windward side of the 4,200 feet long main span of the Suspension Bridge, the west pedestrian railing needed to be replaced with a railing with less solidity facing the incoming wind. The wind climate analysis revealed that extreme wind events at the Bridge site are strongly correlated with strong winds approaching from the west. Therefore, only the west side railing needed to be replaced to improve the aerodynamic stability of the Bridge. The wind retrofit design was based on extensive wind tunnel testing of a scaled model of the Suspension Bridge. The tests showed that, to maintain aerodynamic stability of the Suspension Bridge main span deck truss during strong wind events, it was necessary to increase the transparency of the bridge railing for winds to pass through by replacing the original railing having wide pickets with a new railing having thin pickets. The inclusion of the wind retrofit in Contract No. 2016-B-01 was necessary to mitigate any effect the Physical Suicide Deterrent System could have on the Suspension Bridge's aerodynamic stability.

As the wind retrofit installation progressed, the Bridge began emanating wind-induced sounds during certain high-velocity wind events. On June 5, 2020, during a period of high westerly winds, wind-induced sounds coming from the Golden Gate Bridge were heard at large distances from the Bridge. The sound appeared to be a result of the wind passing through the new west bridge railing.

In October/November 2020 and June 2021, wind tunnel tests commissioned by the District were performed on a full-scale new bridge railing specimen. Based on the test results, it was determined that installing 1/16" thick tapered U-shape aluminum clips with alternating orientation of the clips and with 1/16" thick vibration rubber damping material inserts on both edges of each picket of the new west sidewalk bridge railing for the full length of the main span of the Suspension Bridge is the most effective measure to reduce the sound.

On the Suspension Bridge west sidewalk, this measure would reduce the sound for the majority of wind speed and direction combinations by 10 to 40dB (a 10dB drop reduces the loudness of sound by 50%), and would either eliminate wind induced sound or reduce the sound level to a level no higher than 80dBA (5 dB above the 75dBA ambient sound measured on the Bridge; such sound level would be inaudible to slightly audible), except for four specific wind tunnel wind speed and direction combinations generating the sound level above 80dB when the sound would be audible. Such audible events may occur for no longer than an estimated total of 88 hours a year.

Because the level of sound traveling through air is affected by many factors, e.g., distance attenuation, atmospheric attenuation, topography of the terrain, etc., if sound is generated by the Bridge after the sound reduction measure is installed, at the locations away from the Bridge the sound would be inaudible, except for the above stated four wind tunnel wind speed and direction combinations when the sound would be only slightly audible.

The proposed sound reduction design allows for the clips to be easily fabricated and painted, to be readily installed on the bridge railing pickets (which has been verified in the field), to be durable enough to withstand the harsh environmental conditions at the Bridge, to be relatively easy to maintain, to have a profile that was effective to attenuate the sound but did not alter the appearance of the pickets, and to have no negative impact on the effectiveness of the wind retrofit. It was concluded that tapered U-shape aluminum clips fabricated to precise dimensions to fit over the edges of pickets with added vibration damping rubber inserts would satisfy these requirements.

The rubber inserts also physically separate the aluminum clips from the steel pickets, avoiding galvanic corrosion.

To assess the visual effect of the clip installation on the new west bridge railing, the painted tapered aluminum U-clips with rubber inserts have been installed on one bridge railing panel. The photographs below show side-by-side the railing without the clips on the left and with the clips installed on the right.

Although the color of the mock-up railing panel appears to be a lighter color than the rest of the railing on the above photograph, the color of the clips to be installed will match the color of the railing.

The architectural preservation consultant retained by the District as part of the HDR Engineering, Inc., Professional Services Agreement for the Suspension Bridge Seismic and Wind Retrofit Project, has reviewed the visual effect of the sound reduction measure and determined that the appearance of the pickets with noise-reduction clips will not be noticeable and will not affect transparency of the structure, which is the project's architectural criteria.

The proposed sound reduction measure is a minor alteration of the bridge railing that will not expand the existing facility or alter the current use of the bridge railing as a barrier between people using the sidewalk and the drop from the Bridge beyond the sidewalk edge, nor will it alter the use of the railing as a bridge element that allows wind at the Bridge site to pass through with the least obstruction to assure aerodynamic stability of the Suspension Bridge during high wind events. In addition, the installation of the sound reduction measure will reduce the potential for the railing to create the sound that can arise during certain wind events. The elimination or reduction of the sound is beneficial, does not have the potential for a significant effect on the environment, and will not require major revisions to any prior environmental review. Therefore, the implementation of the mitigation measure is considered categorically exempt under the California Environmental Quality Act (CEQA), because it is a minor alteration to an existing facility under CEQA Guidelines §15301; it is a replacement or reconstruction of an existing structure and facility that serves the substantially same purpose under CEQA Guideline §15302; it is a construction of a new, small structure under CEQA Guideline §15303; it is a construction or placement of a minor structure accessory or appurtenant to an existing facility under CEQA Guideline §15311; and it has no possibility of having a significant effect on the environment under CEQA Guidelines §15061. There are no known particularly sensitive habitats, cumulative impacts, unusual circumstances, or other exceptions to why these exemptions do not apply. If approved by the Board, staff will file the Notice of Exemption with the City and County of San Francisco and the County of Marin.

The implementation of the proposed sound reduction measure will involve contracting for:

- Fabrication of dies to form the aluminum clips and fabrication of approximately 26,000 aluminum clips
- Painting of the clips, and
- Fabrication of 26,000 rubber inserts

The installation of the clips and damping material will be performed by the District's Bridge forces.

Engineering staff has estimated the cost of fabricating and painting of the aluminum clips and fabricating of rubber inserts at approximately $450,000.

Staff recommends that the Building and Operating Committee recommend that the Board of Directors approve the proposed sound mitigation measure as presented in this staff report; approve the addition of the Suspension Bridge Sound Mitigation Project in the FY 2021/22 Bridge Division Operating Budget estimating the project to cost $450,000; and authorize the filing of a Notice of Exemption under CEQA for the Suspension Bridge Sound Mitigation Project.

FISCAL IMPACT

The estimated cost of the Suspension Bridge Sound Mitigation Project is $450,000. It is anticipated that the majority of the expenses will be spent during the current FY 21/22. Sufficient funds are available in the current Bridge Division Operating Budget and any expenses expended in future fiscal years will be budgeted accordingly.

BACKGOUND - WIND TUNNEL TESTING AND DEVELOPMENT OF SOUND REDUCTION MEASURE

In early July 2020, the District engaged the services of HDR Engineering, Inc., the design consultant for the Suspension Bridge wind retrofit, and its subconsultant Rowan Williams Davies and Irwin Inc. (RWDI) with expertise in aerodynamics and acoustics, to investigate which elements of the wind retrofit were participating in the sound generation and what levels and frequency of tones were emanated, and to perform wind tunnel testing and acoustic studies on a full scale specimen of the new bridge railing and fairing in order to replicate, in the laboratory, the wind-induced sound and to determine what modifications, if any, could be made to reduce or eliminate the sound without impairing the effectiveness of the wind retrofit.

As authorized by Board Resolution No. 2020-044, the first series of wind tunnel tests was conducted by RWDI from October 25, 2020 to November 5, 2020. The test specimens were subjected to air flow at various angles and speeds, with a top laboratory wind speed of approximately 67 miles per hour. The tests replicated the low, 400-500 Hz, and the high, about 1.1 kHz, frequency tones, recorded at the Bridge. The tests verified that the sound was generated by interaction between the railing pickets and wind flowing around the pickets. The tests also verified that the railing posts, the top rail and the wind fairing were not engaged in the sound generation.

The wind tunnel tests demonstrated that the low-frequency tone was present when the wind direction was approximately perpendicular to the railing and the tone continuously increased in frequency with increasing wind speed. Therefore, depending on the wind speed, the low tone could span a wider range of frequencies than originally observed at the Bridge. The tests indicated that this tone occurred at frequencies as low as 280 Hz to frequencies as high as 700 Hz. The onset of the low-frequency tone was recorded at a wind tunnel wind speed of approximately 22 miles per hour.

The high-frequency tone of approximately 1.1 kHz was recorded when the wind direction was at an angle of less than 80 degrees to the railing and with no significant change in frequency relative to changes in wind speeds. The onset of the high-frequency tone was recorded at a wind tunnel wind speed of approximately 27 miles per hour.

The two tones did not appear to be correlated as the onset of tones did not occur at the same wind speed and direction and the tone loudness did not increase and decrease simultaneously. The tests have revealed that there are two aeroacoustic noise-generating mechanisms causing the sound. Both mechanisms are related to the pickets of the railing and they are both caused by air flow vortex shedding from an edge of the picket. In general, the low- and high-frequency tones are described to be caused by the following aeroacoustic mechanisms:

- The low-frequency tone (<700 Hz) is caused by an interaction of the railing picket structural vibration modes with vortex shedding from the pickets. As the wind speed increases, the frequency of shedding increases until that frequency matches the frequency of picket structural resonance (vibration mode). At this point a feedback loop occurs increasing both the amplitude of picket vibration and vortex shedding. The pickets then radiate this vibration to the air as a sound (similar to a speaker cone). The low-frequency tones vary with wind speed and are only present when winds are approximately perpendicular (at an angle of 80 to 90 degrees) to the railing pickets. At higher wind speeds, additional harmonics may also appear where the higher vortex-shedding frequency synchronizes with higher vibration modes of the pickets.

Illustration of vortex shedding. As wind flows around the railing pickets (from left to right), the flow oscillates around the obstruction and vortices are shed from the trailing edge of a picket. Note that the vortex shedding mechanism is influenced by flow disruptions at both edges of a picket.

- The high-frequency tone (approximately 1.1 kHz) is caused by an interaction of standing air waves between pickets with vortex shedding from the pickets when the vortex shedding frequencies match the standing wave frequencies. This phenomenon, called "Parker modes" and "Parker Resonances" (Parker, 1967[1]), is purely acoustic and unrelated to any mechanical vibration of the structure. The resonance modes of standing waves are related to the picket spacing and depth. The high-frequency tone appears when the wind impinges on the pickets at a skewed angle of between 10 and 80 degrees to the pickets.

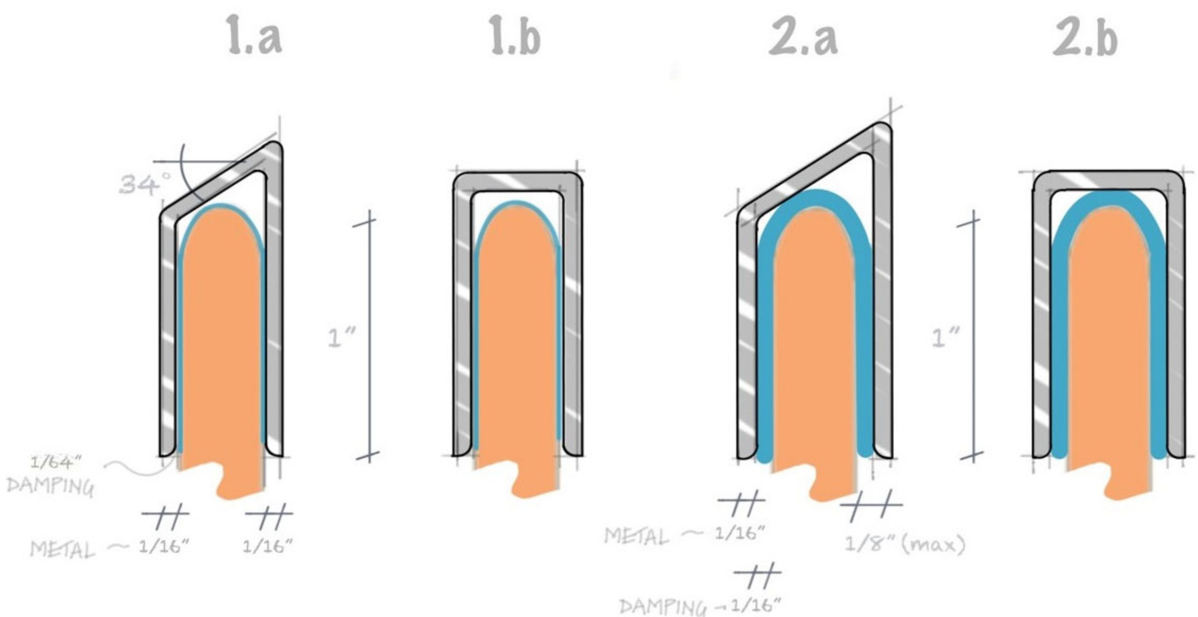
The consultant developed and tested a series of different modifications of the railing to determine the effectiveness of the modifications in preventing the emanation of sound. Potential mitigation options were subdivided into four categories:

1. Structural changes consisting of the addition of horizontal bars attached to the pickets.
2. Disruption of airflow by applying coarse tapes to the edges of the pickets.
3. Disruption of airflow and damping of picket vibration by fitting plexiglass rectangular or angled (chamfered) U-shape clips over the picket leading and/or trailing edges; or by applying anti-vibration viscoelastic textured paint to the wide faces of the pickets.
4. Damping of picket vibration by filling the top rail cavity with metal to increase railing mass and its damping capacity.

One proposed option consisted of U-shape clips fitted over the edges of the pickets, which showed an ability to eliminate or significantly reduce the low and high -frequency tones.
Engineering staff and the consultant reviewed and evaluated the test results and developed U-shape aluminum clip designs (shown below) with vibration damping rubber material inserts. Based on

[1] Parker, R., Resonance effects in wake shedding from parallel plates: Calculation of resonant frequencies, Journal of Sound and Vibration, Volume 5, Issue 2,1967, Pages 330-343, ISSN 0022-460X

the conducted wind tunnel tests, it was anticipated that the clip designs could be potentially effective measures to attenuate the sound, because the U-shape clips would obstruct the formation of vortex shedding, and rubber inserts would damp vibration of the pickets (as such reducing low-frequency tone sound radiation).



Designs of aluminum clips with inserts

In June 2021, the consultant conducted the second series of wind tunnel tests, authorized by Board Resolution No. 2021-043, to verify the sound attenuation capability of the aluminum clips and to determine the most effective configuration of clips installed on the edges of the pickets and with different thicknesses of vibration damping inserts. The wind tunnel testing consisted of performing a baseline test on a full-scale railing panel with no clips or damping material and then to perform tests on 20 clip and damping material configurations installed on the panel to determine the optimal configuration for reducing sound.

All 20 configurations were tested at 11 different laboratory wind speeds (between 22 and 67 mph), and at 10 different wind angles (from 90 degrees to 0 degrees with respect to the railing). To determine the effectiveness of the tested potential sound reduction measures, sound recordings were taken with an acoustic camera (sound level measured in dB; sound frequency measured in Hz). The sound levels generated by the railing specimen with the sound reduction measure were recorded at various wind speeds and angles and then were compared to the recorded levels of sound generated at corresponding wind speeds and angles by the railing specimen without the sound reduction measure.

Subsequent to the laboratory testing, in August 2021, representatives from RWDI conducted a site investigation (1) to perform ambient noise measurements on the Bridge and at the San Francisco Richmond District, (2) to confirm the accuracy of the wind monitor located on the Bridge, and (3) to take additional wind speed and wind direction measurements.

Upon completion of the wind tunnel testing and site investigation, it was concluded that installing 1/16" thick tapered U-clips and 1/16" thick vibration damping rubber material (shown below) on both edges of each picket, the full height of a picket, with alternating orientation of the tapered clips (shown below) for the full length of the Suspension Bridge main span would either eliminate or greatly reduce levels of both the high-frequency and low-frequency wind induced tones for almost all wind speeds and wind directions.

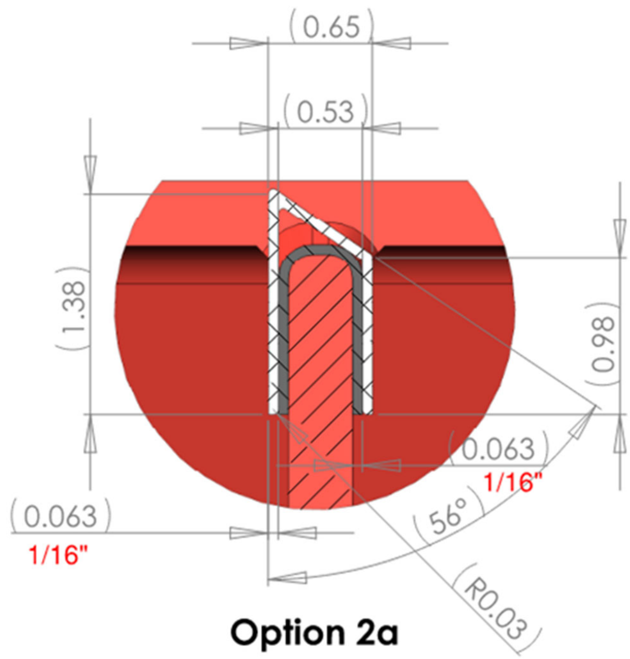


Illustration of the proposed design of clip with insert.

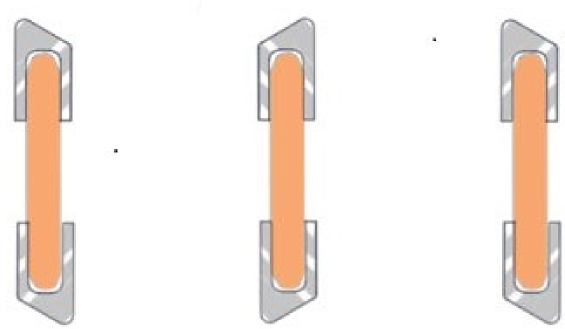


Illustration of the alternating orientation of clips.
(the sketch is not to scale; the size of the clips is exaggerated relative to the size of the pickets)

Sound Reduction at the Bridge Sidewalk. The wind laboratory tests simulated wind conditions on the Bridge sidewalk. The tested wind tunnel air flow velocities covered the range from approximately 22 mph up to 67 mph. Based on the wind climate analysis, the highest wind speed represents a mean wind speed with a 20-year return period at the Bridge site; the highest expected mean hourly wind speed in an average year at the elevation of the bridge railing is 48 mph.

A sound is generally perceived by human ears as noticeable and intrusive if it is greater than 5dB above the ambient sound level. An ambient sound level on the Bridge sidewalk was measured as 75dBA. As such, tonal sounds of up to 80dBA will be inaudible to just audible, but not likely annoying on the Bridge sidewalk.

A drop in a sound level by 20dB is perceived subjectively as a 75% drop in the sound loudness, and a drop in a sound level by 10dB is perceived subjectively as a 50% drop in the sound loudness.

The test results were compared for the railing specimens without and with the recommended sound reduction measure. Each of these specimens was subjected to 110 wind speed and wind direction combinations (11 wind speeds x 10 wind directions). For the railing specimen with the recommended sound reduction measure, the sound was either eliminated or the sound level was decreased by between 10 to 40dB, except for two wind speed and direction combinations where the sound level dropped less than 10dB.

For the recorded sound exceeding 80dB emanated by the specimen with the sound reduction measure, an average annual number of hours for the specific corresponding combinations of wind speed and direction was calculated based on the wind climate analysis.

The below table summarizes results of the 110 wind tunnel tests each for the railing specimens without and with the recommended sound reduction measure.

	Number of Recorded Sound Occurrences with Various Wind Speed and Wind Direction Combinations	
Recorded Sound Level	**Specimen Without the Sound Reduction Measure**	**Specimen With the Sound Reduction Measure**
0dB; no tonal sound	28	43
Tonal sound of less than or equal to 80dB	28	63
Tonal sound of more than 80 dB	54	4

For the mitigated specimen, the 4 recordings of the sound exceeding 80dB were as follows:

- One recording of a low-frequency tone of 87dB occurred at a wind tunnel wind speed of 63 miles per hour with the wind direction perpendicular to the railing. Based on the wind climate analysis, it has been estimated that such events may occur a total of 18 hours on an average annual basis (compared to 8760 hours per year);

- Three recordings of high-frequency tones of 91dB, 94dB and 82dB occurred at a wind tunnel wind speed of between 36 and 45 miles per hour and at the wind direction of 40 degrees to the railing. Based on the wind climate analysis, it has been estimated that such events may occur a total of 70 hours on an average annual basis.

Sound Reduction at a Distance from the Suspension Bridge. Sound levels measured in the wind tunnel before and after the sound reduction applications were used to model sound levels at locations away from the Golden Gate Bridge for worst-case scenarios, where the new Bridge railing is assumed to be emitting sound corresponding to the maximum levels measured in the wind tunnel. The modelling took into account the following factors:

- source sound power level and directivity;
- distance attenuation;
- ground (topography) and air (atmospheric) attenuation;
- source-receptor geometry including heights, elevations, and topography;
- barrier effects of the site and surrounding buildings;
- duration of events; and,
- meteorological effects on sound propagation.

RWDI recorded several measurements of background (ambient) sound to confirm that the residential areas near the Golden Gate Bridge meet a typical approximately 50 dBA suburban acoustic environment. Sound levels after the installation of the sound reduction measure are predicted to fall significantly below that of background levels (more than 10 dB below the typical background). Based on the noise modeling results and background sound level in the surrounding neighborhoods, if sound is generated by the Bridge after the sound reduction measure is installed, at the locations away from the Bridge, the sound would be inaudible, except that, for the above stated four wind tunnel wind speed and direction combinations generating sound levels above 80dB on the Bridge, the sound would be only slightly audible at the locations away from the Bridge.

As a note, at a location near the source of a sound (e.g., on the Bridge sidewalk), propagation occurs in all directions with little influence from environmental factors. However, there are several additional factors affecting loudness at locations far away from the source (e.g., at the surrounding neighborhoods). When sound is travelling through air, the sound level far away from a source will depend on the temperature, humidity, atmospheric pressure of the air, and on the frequency of the travelling sound. Sounds with higher frequencies are absorbed by the air to a greater extent than lower frequencies. As such, it can be said that for any given atmospheric conditions, a lower-frequency sound will be audible further away, despite similar sound levels near the source of the sound. Hence, the high-frequency tone emitted by the bridge railing will be absorbed to a greater extent than the low-frequency tone. Even when both tones are emitted by the railings at a similar level, the lower-frequency tone will be less absorbed and consequently of greater loudness at locations surrounding the Golden Gate Bridge. It is therefore not surprising that the lower-frequency tone (e.g., a 440 Hz tone) is the dominant tone typically recorded at a distance from the Golden Gate Bridge.

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