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"Statistical Analysis of Extreme Wind Speeds in the Straits of Messina"

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Statistical analysis of extreme wind speeds in the Straits of Messina

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Summary

This paper illustrates the methods for the statistical analysis of extreme wind speeds, drawn up on the occasion of the preliminary design for the construction of a bridge over the Straits of Messina. The studies are based on two alternative approaches, each one constituting a verification and control element for the other, leading to sound and generally reliable assessments. With the possibility existing for further improvement, the actual quality of the results obtained suggests that the procedures established could be applied to any situation.

1. Introduction

The design and construction of a bridge over the Straits of Messina, a structure of outstanding importance and susceptibility to wind, first requires an accurate and reliable study of the parent population and extreme wind distributions over the site. In meeting this need, however, there are various problems that render such an assessment anything other than easy.

The nearest anemometric station, constructed by the company Stretto di Messina (SM) at Punta Faro about 2 km from the center of the proposed bridge, supplies important elements regarding the space–time configuration of the design winds [1]. As this station has been in operation only since 1985, the amount of information collected is insufficient for the statistical analysis of the distribution of extreme winds.

ITAV (Air traffic control and telecommunications board, of the Italian air force) and ENEL (National electricity board) weather stations in the area around the Straits supply data recorded over much longer time periods, but are very far from the site: the nearest, Messina, is about 12 km away. In addition,

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these stations are positioned in locations which are too dissimilar, so that the information collected cannot be used without any prior accurate conversion.

Unfortunately it happens that the extreme orographic complexity of the area under examination renders the classic conversion procedures unusable. In fact, the commonly used theoretical models often fail when dealing with this conformation of the ground [2].

Moreover, the topographic wind tunnel tests in this situation do not guarantee sufficient reliability. Since the circulation regimes around the Straits are greatly influenced by the Sicilian and Calabrian orography, the realization of a physical model truly representative of the wind would require the use of an exceptionally large scale. Such scales in fact do not allow reliable interpretation of measurements taken at ground level (where the majority of the available instruments are located), thus precluding the possibility of establishing efficient transformation laws.

In the light of these observations, bearing in mind the need for a study of high reliability, a coordinated research project was started jointly by the Department of Mechanics at Milan Polytechnic and the Institute of Construction Science and the Department of Physics, both at Genoa University. The lines of research are based on two alternative methods here called "correlation analysis" and "simulation analysis". Each of the two approaches to the problem also acts as a verification and control for the other.

The correlation analysis [3], carried out at the Milan Polytechnic Department of Mechanics, provides a preliminary assessment of the existing correlation between anemometric measurements recorded at Punta Faro and those recorded at other stations in the area of the Straits during the same period. The results obtained are used to supplement the Punta Faro data base for the period in which the latter was not operational. This allows a more reliable study of the extreme wind speeds to be undertaken.

The simulation analysis [4,5], carried out in close collaboration between the Institute of Construction Science and the Department of Physics at Genoa University, makes use of a preliminary implementation of a wide range of numerical models of the Straits or its parts. On the basis of these models, the measurements taken by the individual stations are transformed into wind speeds at the bridge. These are then used to develop the statistic inference analysis.

This paper provides a synthesis of the methods formulated and results obtained in [3–5]. It furthermore discusses the potential of the procedures elaborated for use in more general situations.

2. Weather stations and data recorded

The following analyses are based on the wind speeds V_A and directions α_A, averaged over 10 min intervals, measured in 12 weather stations located around the Straits of Messina. Table 1 shows the main characteristics of the stations selected. Figure 1 illustrates their geographic position.

Table 1

Main characteristics of the stations selected

Weather station	Board	Coordinates		Height (m) above sea level	Anemometric height (m)	Period (years)	Data
		Latitude	Longitude				
Stromboli	ITAV	38 48′	15 15′	5	10	1953–1975	b
Ginostra	ENEL	38 48′	15 10′	130	12	1984–1988	a
Ustica	ITAV	38 42′	13 11′	251	10	1951–1990	b
Filicudi	ENEL	38 35′	14 34′	278	12	1986–1988	a
Salina	ENEL	38 35′	14 49′	283	12	1985–1989	a
Barrittieri	ENEL	38 19′	15 50′	530	15	1985–1990	a
Punta Faro	SM	38 16′	15 38′	≈0	d	1985–1990	a
Messina	ITAV	38 12′	15 33′	59	19	1951–1988	b
Reggio Calabria	ITAV	38 04′	15 39′	11	10	1951–1988	c
Capo Spartiv.	ITAV	37 55′	16 04′	118	15	1951–1978	b
Catania F. Rossa	ITAV	37 28′	15 03′	8	10	1951–1990	b
Pantelleria	ITAV	36 49′	11 58′	170	6.5	1951–1990	b
Cozzo Spadaro	ITAV	36 41′	15 08′	40	11	1951–1973	b

[a]Sampling every 10 min.
[b]Sampling during 10 min before synoptic hours.
[c]As b, but without night hours.
[d]64, 78, 92, 128, 164, 232 m above sea level.

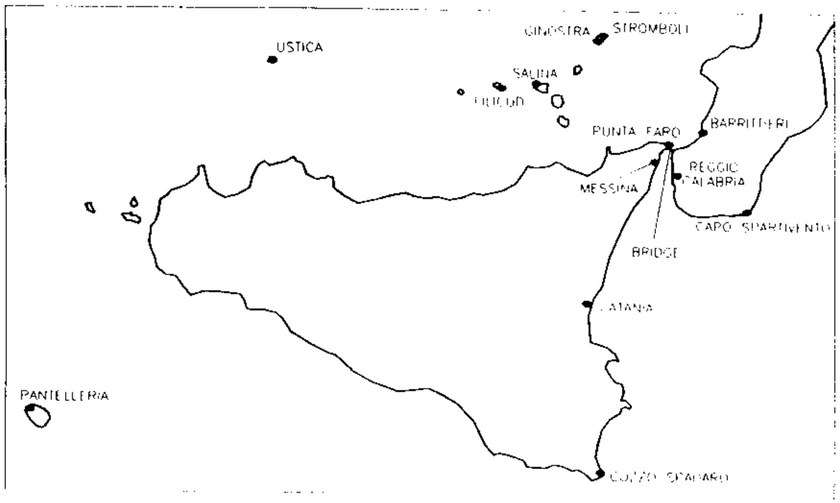

Fig. 1. Geographic position of the stations selected.

The data acquired in each station are processed and corrected according to the procedures in Ref. [2]. The statistical analysis of the correct data bases [3,5] shows a profound dissimilarity between one station and another. This is caused by the differences between the anemometers in relation to their height above ground level, local and global orographic conditions and the roughness of the terrain where the unit is located.

3. Correlation analysis

The correlation analysis is based on the following procedure:

(i) Analysis of the data recorded at the Punta Faro station.

(ii) Study of the correlation between the anemometric data recorded by all the stations in particular wind situations.

(iii) Directional analysis of the extreme winds recorded at the stations that show, for a given direction sector, a higher degree of correlation with Punta Faro.

(iv) Directional statistical study of extreme winds at Punta Faro, and then at the bridge, performed by processing the correlation estimates.

Figure 2 shows a diagram reporting the cumulative probability of wind speeds higher than 15 m/s recorded by the Punta Faro anemometer, 92 m above sea level, as a function of the month of the year and the direction. From an analysis of this diagram, and a general study of the data recorded at Punta Faro during the years this station has been operational [1], it results that:

(i) The more frequent strong winds blow from SW, predominantly in spring, and then from S, predominantly in the winter months.

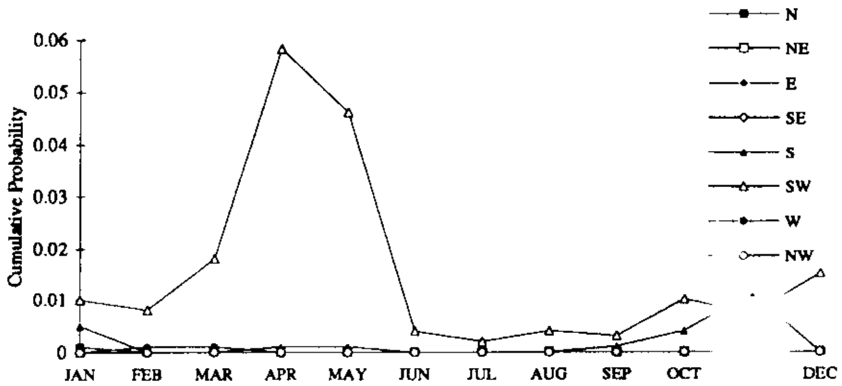

Fig. 2. Cumulative probability of wind speeds higher than 15 m/s recorded by t[illegible]a Faro anemometer 92 m above sea level.

(ii) The N and NW sectors are characterized by a very low frequency, concentrated during the winter months, but with an intensity generally higher than that of winds blowing from the southern quadrants; moreover it happens that the north winds are not frequent and are, above all, characterized by a rather low average speed; consequently they cannot be considered as meaningful for a final correlation study.

(iii) Winds from other sectors are almost non-existent.

As the anemometric stations are located over a particularly wide area, the study of the correlation between the different anemometric recordings must also take into account the evolution of the meteorological conditions that cause the strong winds. In particular, these depend on the pressure of the cyclonic circulation nuclei, their pressure gradient and their position.

The correlation analysis of the anemometric data requires, therefore, a preliminary study of the meteorological situations that generate strong winds, in order to verify their congruence with the recordings from the individual stations.

The procedure allows:

(i) Maximum speeds recorded, even if not simultaneously, at different stations, even several miles apart, to be attributed to a general meteorological situation.

(ii) Events due to local meteorological phenomena to be excluded from the analysis.

(iii) To assess the average ratios between the speeds recorded in the various stations and the corresponding speeds recorded at Punta Faro.

(iv) To assess the average differences between the directions recorded in the considered stations and those recorded at Punta Faro.

3.1. *Southerly winds*

In the analysis of winds from the southern quadrant, the data recorded by the station at the Tito Minniti airport, near Reggio Calabria, approximately 25 km south of Punta Faro, appear to be the most correlated with the data recorded at Punta Faro. This is probably due to the fact that the orography of the flanks of Sicily (the Peloritani mountain chain) and of Calabria (Aspromonte) causes channeling of the air masses that blow from the south. It can also be seen that the south-west winds at Punta Faro blow from the South at Reggio Calabria. This rotation is due to the orographic effects of the Straits and is true for all southerly winds. Note that, from these sectors, the Sirocco (SE) and Libeccio (SW) winds are the strongest. The Sirocco winds are mainly due to the formation of a low pressure zone with its nucleus at latitudes below Sicily, or the drawing of the air masses towards the deep low pressure centers of northern Europe. The Libeccio winds are, instead, formed by the movement of a cold front from the sector between west and north-west.

The following method is used to estimate the correlation between the data recorded at Punta Faro and Reggio Calabria:

(i) All winds of a speed greater than 15 m/s recorded at Punta Faro are retained.

(ii) Readings with more than a 1 h delay with respect to the ITAV measurements or winds for which there are no corresponding or reliable measurements from Reggio Calabria, are eliminated (for example, winds of an average speed less than 5 m/s are not taken into consideration).

(iii) For data recorded at Punta Faro less than 1 h after the Reggio Calabria readings, the maximum value is considered: this maximum and its corresponding direction value are used to determine the mean of the ratios between the speeds and the mean of the differences between the directions.

The following conclusions are reached:

(i) The average ratio between the corresponding wind speeds measured at Reggio Calabria and Punta Faro is equal to 0.54; the standard deviation of this ratio is equal to 0.04;

(ii) The average difference between the corresponding directions measured at Reggio Calabria and Punta Faro is equal to −25°; the standard deviation of this difference is equal to 25°.

3.2. Northerly winds

A systematic analysis of the weather situations which produce meaningful northern winds in the southern Mediterranean has been carried out. Starting from these situations a further analysis has been developed in order to evaluate the correlation existing between wind speeds at Punta Faro and in all other weather stations. The results of this analysis demonstrates that the winds recorded at Ustica are the most correlated with those measured at Punta Faro.

For example, Fig. 3 shows the ground weather maps for 31 December 1979 and 1 January 1980 when the Mistral winds were the strongest ever recorded at Punta Faro [1]. It can be seen that the low pressure cyclonic nucleus moves from the Danish peninsula to the Balkans. This movement causes the direction of the wind to rotate from west to north and to intensify due to the increase in the pressure gradient. In addition, it appears that the barometric values at

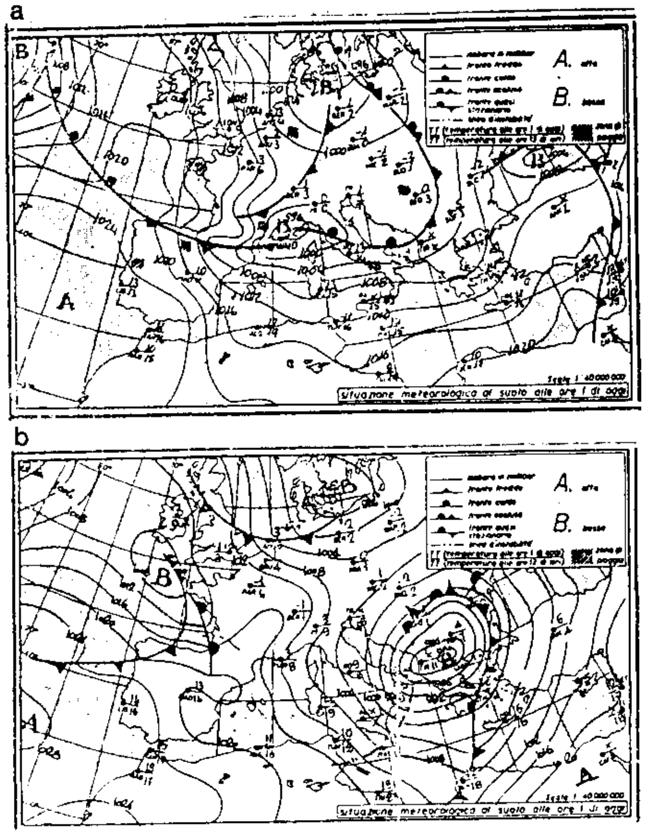

Fig. 3. Weather maps at ground level: (a) 31-12-79; (b) 1-1-80.

Punta Faro and Ustica are very similar. These observations can be confirmed from an analysis of the time histories reported in Fig. 4, where the change in direction of the wind and its intensification are evident. Furthermore, as there is no appreciable delay between the recordings, they can be said to be closely correlated.

From these observations, and taking into account the most meaningful events that occurred at Punta Faro between 1985 and 1990, the following conclusions can be drawn:

(i) The average of the ratios between the wind speeds measured at Ustica and Punta Faro is equal to 1.09, with a standard deviation equal to 0.09;

(ii) The difference between the directions cannot normally be correlated to the orography of the Straits. A clear correlation becomes evident only in the case of exceptionally strong winds.

The directional estimation of extreme wind speeds measured by the Reggio Calabria and Ustica meteorological stations is carried out using the method outlined in Ref. [6].

The values obtained are then corrected according to the procedure described in Ref. [5], in order to take into account the different data acquisition characteristics of the ITAV and Punta Faro stations.

The results of the correlation analysis and the estimations of the extreme wind speeds are finally used to calculate the average speed of the winds at Punta Faro corresponding to the mean return periods established for the design of the bridge. These values are then carried to the deck level of the bridge at 64 m.

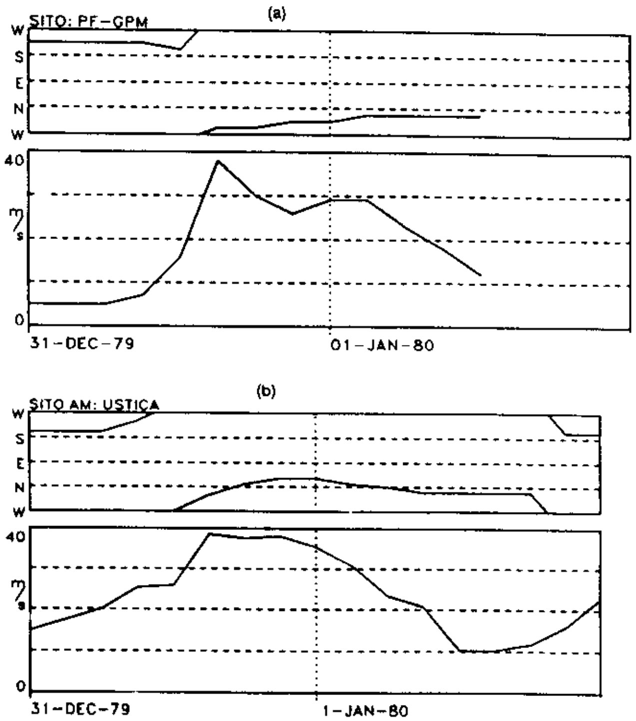

Fig. 4. Wind direction and speed since 31-12-1979 to 1-1-80: (a) Punta Faro; (b) Ustica.

Table 2

Extreme mean wind speeds at the bridge centerline as derived from the correlation analysis

$\bar{R}$ (years)	V_P (m/s) SW sector	V_P (m/s) NW sector
50	35.7	37.8
400	42.1	45.7
2000	46.9	51.8

Table 2 summarizes the results of this study expressing the extreme mean wind speeds in the center of the bridge (V_P) as a function of the mean return period $\bar{R}$ and the direction from which the wind blows.

4. Numerical modeling

The WINDS code (Wind field Interpolation by Non Divergent Schemes) for the determination of three-dimensional wind fields over a complex area has been set in the Climatology Laboratory of the Department of Physics at Genoa University [7,8] starting with the NOABL [9] and AIOLOS [10] codes. The model, which is basically mass consistent, is initialized with a wind field estimated from the data recorded in ground level observation stations and/or from gradient wind. It then constructs a non-divergent wind field using a numeric resolution process. This field is obtained from an equation deduced from the minimization of the quadratic differences of the final field from the initial field, while respecting the continuity equation [9,11-13].

The principal limitations of the WINDS model, as with all mass-consistent models, derive from the elimination of all physical restraints except for the conservation of mass. It follows then that these models are not capable of simulating phenomena such as breezes, mountain valley winds, effects caused by the presence of heat islands. These phenomena may only be considered in the simulations if included in the initial anemologic data and observed at the sites. This does not constitute a problem, however, in this research: as this study is aimed at analyzing extreme winds, local phenomena are of marginal importance. What is important, instead, is the forcing effect induced by the orography of the ground.

The fundamental characteristics of the WINDS code can be grouped into the following four aspects:

(1) The initial motion field is constructed assuming that the wind has, at an altitude corresponding to the upper edge of the atmospheric boundary layer, a gradient wind speed V_G and direction α_G, both constant for the whole area simulated.

(2) The directional variations of the wind speed vector with altitude is caused by the Coriolis force: therefore, the speed vector follows the Ekman spiral.

(3) The roughness coefficient z_0, which describes the roughness of the ground, is evaluated for the individual nodes of the calculation grid.

(4) The conditions of atmospheric stability are made to vary as a function of the value given to the Monin–Obukov length; a parameter capable of "forcing" the wind to "pass round" or "pass over " the obstacles, according to whether the atmosphere is stable or unstable, is associated to this length.

For this particular study, the WINDS code is applied in its standard version, which does not include the generation of the internal boundary layer produced by the variations in roughness nor the simulation of separation phenomena downwind of obstacles with steep gradients. Both these options are at present in the perfection and study stages.

The area simulated includes approximately half of Calabria and a third of Sicily, centered around the Straits of Messina (Fig. 5). The area also includes Mount Etna, as its influence on the wind field is quite evident. The zone is discretized by a horizontal grid of 144 × 128 nodes, with spacing of 1200 m east-west and 1150 m north-south. The vertical discretizing is obtained through 10 conformal surfaces. The steeper slopes are represented by Mount Etna in Sicily and Aspromonte at the lower extremity of Calabria. Significant discrepancies may occur in these particular zones between the simulated and effective values.

The ground roughness coefficients (Fig. 6) are defined, through cartography and photogrammetry by the IGM (Military Geographic Institute), applying the tables found in available literature [14,15]. The values supplied are overestimated in order to compensate for poor resolution of the irregularity of the small scale caused by the large size of the grid.

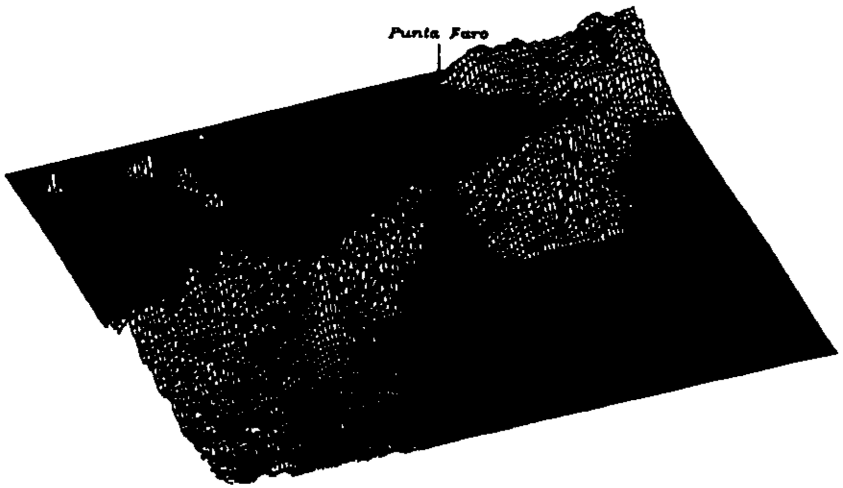

Fig. 5. Numerical modeling of the orography of the area simulated.

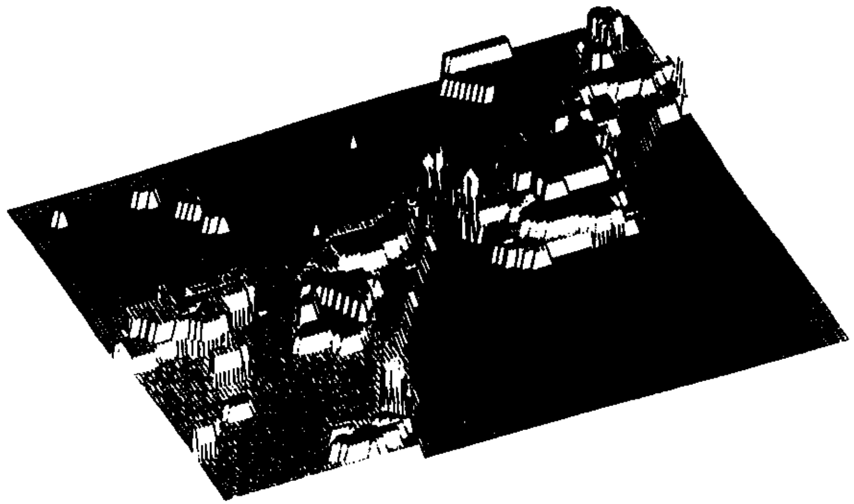

Fig. 6. Numerical modeling of the ground roughness of the area simulated.

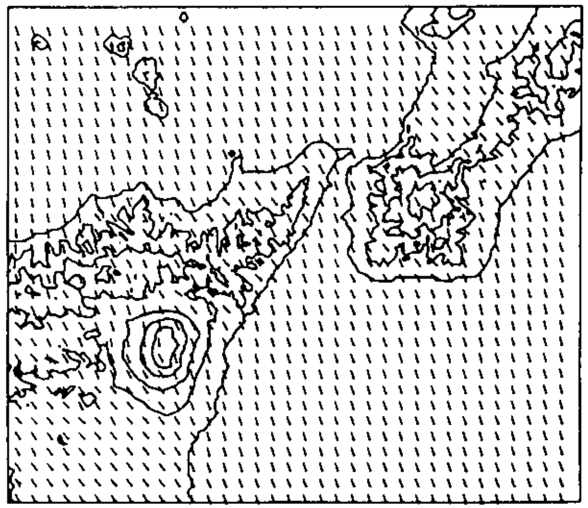

Fig. 7. Wind field in the Straits, at 10 m above the ground, for neutral atmosphere and gradient wind blowing from North.

In addition to the general model of the area of the Straits, three independent models are used for the islands of Salina, Filicudi and Stromboli, where anemometers, strategically located for the study, exist. The discretization uses square horizontal grids of 75 m sides, with 105 × 84, 76 × 62 and 76 × 72 nodes, respectively. The vertical discretizing is obtained through 10 conformal surfaces. The orography and roughness of the ground are assigned without the overestimation criterion illustrated above.

All the wind field simulations are carried out with gradient speed V_G varying from 10 to 100 m/s for 12 different wind directions α_G ($\alpha_G = 0°, 30°, \ldots, 330°$), under three different stability conditions ("neutral", "slightly stable" and "stable" atmosphere). Figure 7 shows a typical wind field over the entire area of the Straits.

5. Simulation analysis

The WINDS calculation program, described in the previous paragraph, and more simply abbreviated as "W" from here on, allows simulations of wind flow at a scale ~10/100 km as a function of the orography of the terrain. When utilized in this context, it precludes the possibility of a precise local representation of the roughness, fundamental in the vicinity of the instrument sites.

It is for this reason that a second calculation program is used, the ES87006 code [16], from here on abbreviated with the letter "E". This program receives a mean reference speed V_R and direction α_R as input data (that is, the value that an ideal anemometer would read if positioned 10 m over the ground level, on uniform flat terrain with a roughness coefficient $z_0 = 0.07$ m). The program outputs the mean speed V_E at any point of a two-dimensional model (in a vertical plane) of the roughness of the terrain allowing at the most to simulate a simple topographic relief. Consequently, although not taking into account the global aspects of the wind circulation in the area of the Straits, it does allow, due to the use of an extremely refined algorithm for roughness transitions, for extremely accurate local simulations.

As a result of their complementary features, the W and E models are applied together, in the hypothesis of neutral atmosphere, according to the following procedure:

(1) Two descriptions of ground roughness in the format required by code E are established. The first (S/W) reproduces the roughness assigned for code W. The second (S/E) reproduces the effective roughness of the terrain.

(2) The mean speeds V_A^* that the different anemometers would have recorded if instead of being located in the actual S/E locations, where they measure V_A and α_A, they had been located in the S/W context, are determined by applying code E to the S/W and S/E schemes. Furthermore, the mean directions α_A^* associated to the V_A^* values are calculated by applying criteria [17].

(3) The results of the analyses described in the previous paragraph are used to determine the mean gradient speeds and directions V_G and α_G, corresponding to the values V_A^* and α_A^*.

(4) The reference values V_R and α_R corresponding to the gradient values V_G and α_G are calculated by re-applying criteria [17]. From the analyses carried out in the preceding points, the measured values V_A, α_A are also calculated.

(5) Values V_A and α_A, are transformed in values V_R and α_R.

The reliability of the transformation models used is verified first by analyzing the correlation between wind data recorded simultaneously at different sites, and then comparing the probability distributions of the values V_R and α_R associated to different stations where the data are recorded [5,18].

Starting with values V_R and α_R, the average wind speeds and directions V_P, α_P at an altitude of 64 m at the bridge centerline are then determined, applying the above transformation procedures in reverse order.

Figure 8 illustrates the complements to 1 of the joint distribution functions of (V_A, α_A), (V_R, α_R) and (V_P, α_P), relating to the stations of Messina and Salina. The points belonging to the inner diagrams correspond to the average wind speed (m/s) within a 30° sector, with an exceeding probability of 1%. The outer diagrams correspond to the exceeding probability of 0.1%, 0.01%, 0.001% and 0.0001%, respectively. It is quite easy to see that, starting with very different initial-distributions V_A and α_A, it is possible to arrive at quite comparable distributions of V_R and α_R, and of V_P and α_P.

Figure 9 shows the probability distributions of the maximum annual value of V_P corresponding to the five anemometric stations (Salina, Messina, Reggio Calabria, Catania, Cozzo Spadaro) for which the transformation process was successful with regard to the distribution of the ordinary values. The various diagrams correspond to different estimation criteria [5,18].

Over and beyond the overall agreement between the extreme wind distributions reported in the above figures, it should also be mentioned that these derive from data not yet thoroughly homogeneous. While the Salina station, in fact, records the average speed and direction of the wind continuously (even if for a relatively short period), the stations of Messina, Reggio Calabria, Catania and Cozzo Spadaro, instead, record the same values over 10 min every 3 h. While the above has clearly no influence on population probability distributions, it could question the validity of the analyses carried out on the extreme wind distributions. In fact, in general, it happens that the assessments regarding Messina, Reggio Calabria, Catania and Cozzo Spadaro do not refer to the maximum annual value, but, instead, to the maximum annual measured value.

In order to correct the above inconsistency, the speeds V_P reported in Figs. 9b–9e have been amplified by a 1.10 factor, as explained in Ref. [5]. Table 3 and Fig. 10a, summarizing the results of this operation (by indicating the mean value, the standard deviation and the variation coefficient of the individual estimations of V_P with $\bar{V}_P$, σ_{VP}, V_V), confirm that this has the effect of rendering the assessments carried out at the bridge definitely homogeneous.

The directional analysis of the extreme wind speeds is carried out by applying the procedure proposed in Ref. [6]. This expresses the average speed of the wind coming from α_P with a mean return period $\bar{R}$ through the formula

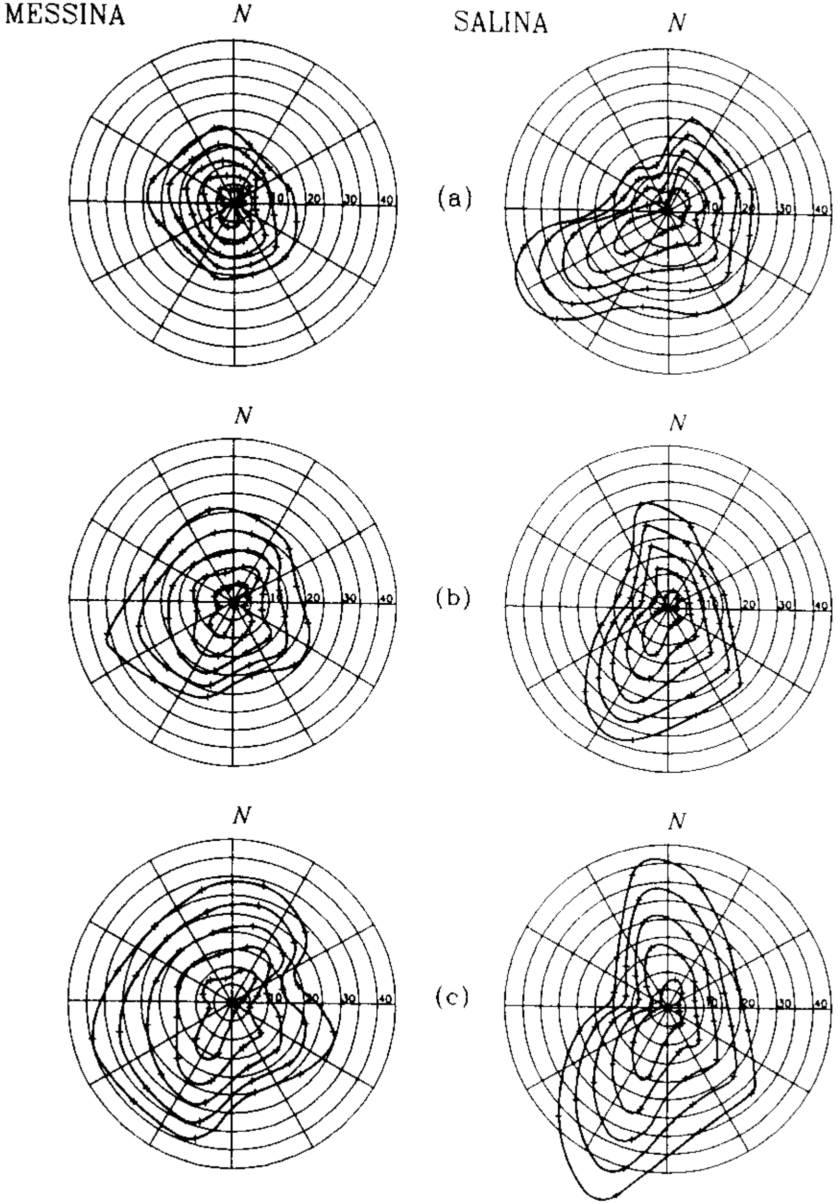

Fig. 8. Joint probability distributions of wind speeds and directions: (a) anemometric records; (b) reference values; (c) estimates at bridge centerline.

$V_P(\alpha_P,\bar{R})=\bar{V}_P(\bar{R})C(\alpha_P)$, where $\bar{V}_P(\bar{R})$ is the average non-directional speed of the wind with a mean return period $\bar{R}$ (Fig. 10a), and $C(\alpha_P)$ is the directional coefficient in Fig. 10b ($\bar{C}$, σ_C being the mean value and the standard deviation of C). As can quite easily be seen, the more intense winds blow from the 180°–240° sector. The less strong winds have, instead, a direction of 60°–120°. The major uncertainties concern the winds coming from the 60°–120° and 300°–330° sectors.

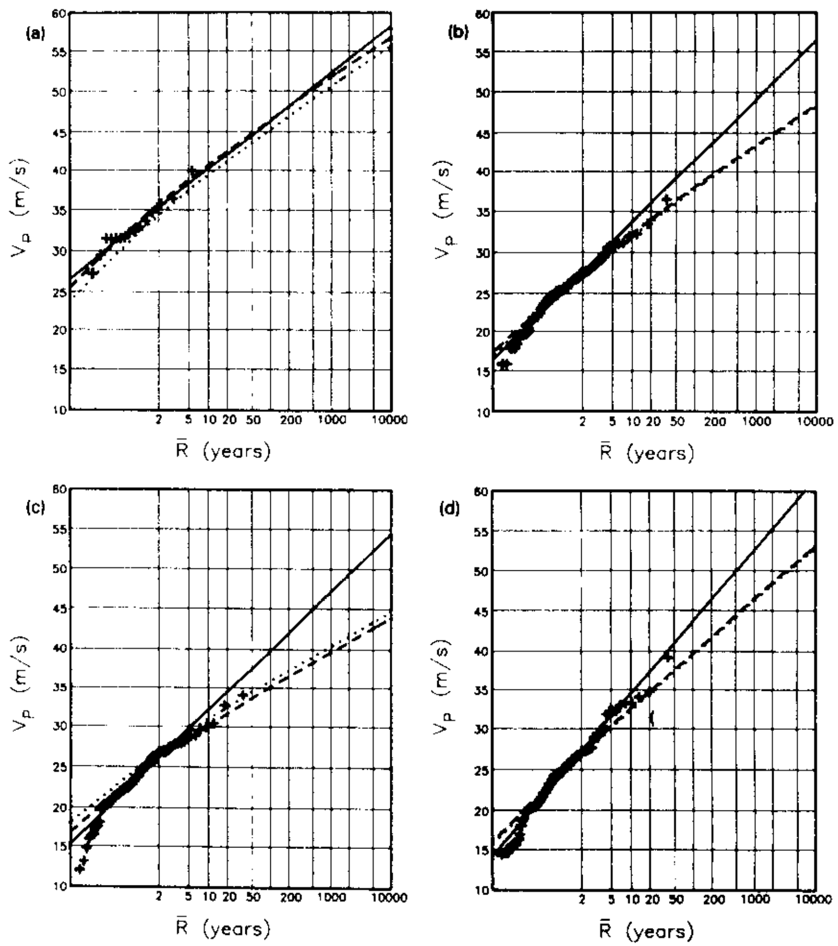

Fig. 9. Probability distributions of the maximum annual value of V_P corresponding to: (a) Salina; (b) Messina; (c) Reggio Calabria; (d) Catania F. Rossa; (e) Cozzo Spadaro.

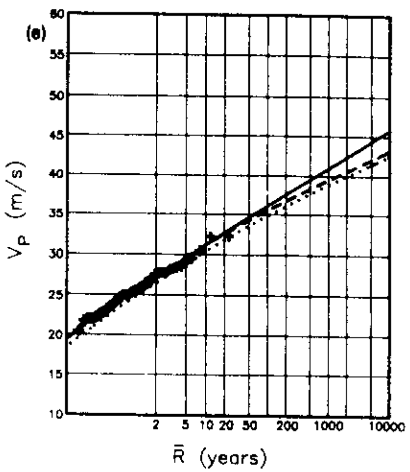

Fig. 9. Continued.

Table 3

Extreme mean wind speeds at the bridge centerline as derived from the simulation analysis

$\bar{R}$	V_P (m/s)					$\bar{V}_P$	σ_{VP}	V_V
(years)	Salina	Messina	Reggio C.	Catania	Cozzo S.	(m/s)	(m/s)	
10	40 41	34	33 34	35	33 34.5	35.9	2.9	0.08
20	42 43	36	34.5 35	37.5	35 36	37.8	3.0	0.08
50	44 45	38	36 37	41	36 38	39.9	3.2	0.08
100	46 47	40	37.5 38.5	43	37.5 39	41.7	3.4	0.08
200	48	41.5	39 40	45	39 40	43.3	3.4	0.08
500	50 51	44	40.5 41.5	48	40 42	45.6	3.8	0.08
1000	52	45.5	42 43	50	41.5 44	47.2	3.8	0.08
2000	53 54	47	43 44	52.5	42.5 45	48.7	4.1	0.08

The comparison between the results of the correlation and simulation studies shows a close agreement relative to the extreme winds coming from the south-west sector. With regard to the north-east winds, the simulation analyses produce slightly lower wind speeds than those obtained from the correlation analyses. This is probably due to the substantial distance of the bridge from Ustica in the context of the correlation study.

Finally, a noticeable fact emerges: the simulation studies confirm the channeling of the ordinary winds at right angles to the centerline of the bridge, as shown by the anemometric measurements taken at Punta Faro. These studies

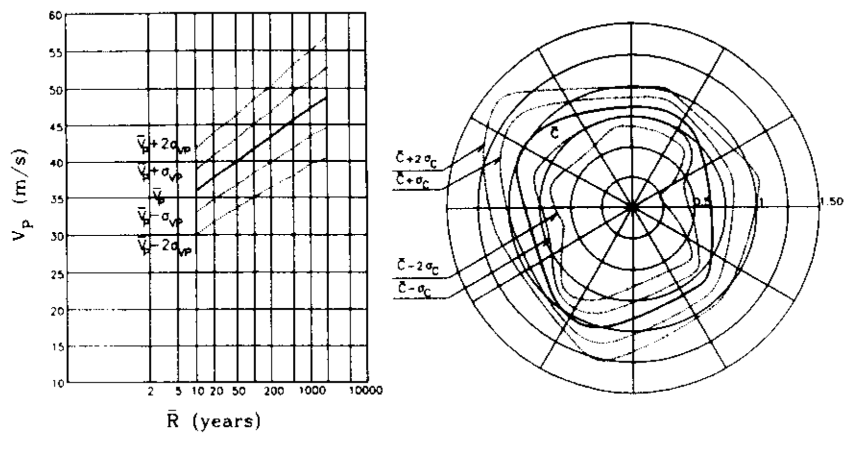

Fig. 10. Extreme mean wind speeds at the bridge centerline: (a) non-directional values V_P; (b) directional coefficient C (α_p).

also show the appearance of extreme winds of high intensity coming from the south-east sector and especially from the north-west sector, winds parallel to the bridge which the correlation studies understandably, due to their conception, do not pick up. Even taking into consideration the fact that these winds are of marginal importance for the design of the bridge, it would, in any case, be rather interesting to try and discover whether they actually exist or are purely a result of the numerical models.

6. Conclusions and prospectives

This paper summarizes the procedures established for evaluating the average speed of the design wind on the proposed bridge over the Straits of Messina. The cross checks and confidence tests on the assessments produced indicate that the solutions obtained are generally constant and fundamentally sound. The agreement between the correlation and simulation analyses is excellent with reference to south-west winds, acceptable for north-east winds. The differences characterizing the south-east and north-west winds, although not meaningful for the design of the bridge, deserve further evaluations.

There is still, however, substantial room for improvement with regard to both the correlation study and the simulations.

With regard to the correlation studies, further research, above all into the Mistral (NW) winds, would seem to be opportune.

The results of the simulations, instead, could be further improved by proceeding in two different directions. On the one hand, the WINDS code could be re-applied by utilizing the "zoom" technique [19] above all around the bridge, simulating the separation in the steeper zones, and modeling the occurrence of the internal boundary layer. On the other hand, more refined statistic criteria [20], deemed as being unnecessary in this context due to the approximations involved, could be adopted.

In any case, a more accurate study of the confidence intervals of all the assessments made would be appropriate.

In view of the general nature of the methods formulated, the authors wish to emphasize the possibility of applying these criteria to the statistical study of winds at any complex site where the anemometric measurements are available in neighboring zones.

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